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Dr. Warkentin

Published literature about six Pacific Northwest stream systems was contrasted to provide a regional perspective on channel response to disturbance. This investigation was prompted by a combination of recent environmental legislation, mounting social pressures to plan projects at a drainage basin scale, and the difficulty in defining and predicting the response and recovery of a stream channel to land-use management or storm events.

Detailed studies of Redwood Creek, CA; the San Lorenzo River, CA; the South Fork Salmon River, ID; the Upper Middle Fork of the Willamette River, OR; the Alsea River System, OR; and Carnation Creek, B.C. were reviewed and contrasted. Differences in channel response to disturbance appear to be the result of the sequence of storms, the interactions between storms and land-use, the processes that deliver sediment to the channel, the available stream power, and the bank stability. Basins

with low debris avalanche and earthflow potential, high stream power, and stable stream banks experience only localized and short-lived response to disturbance. On the other hand, basins with frequent debris avalanches or high earthflow potential and unstable banks experience widespread and persistent response.

This study concludes that there must be realization and acceptance of the random nature of channel response and recovery following disturbance. Field evaluation, professional judgement, risk assessment, and adaptive management are the most powerful tools available in the prediction of channel response.

A Comparative Analysis of Stream Response to Disturbance in the Pacific Northwest

by

Terry Anne Hodgins-Carlson

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Typed by Terry Anne Hodgins-Carlson

To Tom and Duncan, my friends, confidants and support during this endeavor.

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INTRODUCTION

Streams are conduits by which water and hillslope material moves from the mountains to the oceans. System elements, such as riparian vegetation and channel form are constantly adjusting to the dominant erosional and resisting forces, as well as to the fluxes of mass and energy. Channel responses such as changes in channel geometry or hydraulics, will vary with the magnitude, frequency, and spatial distribution of the applied stress.

Most research has focused on case studies in individual basins or isolated anthropogenic or natural disturbance events. There is a lack of published information that synthesizes these studies on basin processes and behavior and examines them in a broader context. The importance of this study is in the synthesis of this information. Synthesis involves placing existing basin studies into a conceptual framework based on hillslope and stream characteristics in order to build a foundation for analyzing the effects of disturbance and predicting basin response.

The objectives of the study are:

1. To ascertain if there are common regional patterns in the ways that channels respond to disturbance.

2. To determine if different mechanisms of water and sediment delivery to a stream produce distinct types of channel response.

NATURE OF THE PROBLEM

Drainage basins result from the interactions among climate, weathering, soil formation, geomorphic processes, streamflow, and biological and chemical processes. Stream systems are constantly adjusting to the dominant erosional (gravity) and resisting forces (vegetation, geology). The importance of, and impediments to, understanding and predicting stream response to disturbance is based in the political and social arena, as well as in the physical environment (Geppert et al, 1984; Cobourn, 1989). As used in this paper, disturbance is a change in the characteristics or processes working within a basin caused by natural or anthropogenic stress. Disturbance is discussed in greater detail in the subsection titled "Disturbance".

Most research on how channels and watersheds respond to land-use and storms has focused either on individual basins, e.g., Carnation Creek (Scrivener, 1987a), or on isolated storms, e.g., the regional analysis of the effects of the 1964 flood across western Oregon (Portland District Corps of Engineers, 1966). Few studies have actually synthesized the results from these individual studies to evaluate system behavior from a broader perspective in order to understand process similarities and differences among basins (Nolan and Marron, 1985; Newson, 1980; Kochel, 1988).

The premise of this study is that the information contained in these existing basin studies can be used to build a foundation for analyzing the effects of disturbance and to predict channel change. This chapter will provide insight into the historical and legal perspectives of disturbance effects analysis. In addition, the principles of disturbance and channel response will be discussed.

HISTORICAL AND LEGAL PERSPECTIVES

During the 1960's and 1970's, public awareness increased regarding the management of forest and other natural resources (Anderson et al, 1984). The National Environmental Policy Act (NEPA), The National Forest Management Act (NFMA) of 1976, and the Clean Water Act of 1977 were the result of this awareness (Anderson et al, 1984).

NEPA, PL 91-190, requires environmental issues to be considered in the land management planning and decision making process, the disclosure of environmental consequences and alternatives as they relate to proposed projects, and public participation in the planning process. NFMA, PL 94-588, was written to insure the consideration of all renewable resources in the planning process. The 1977 Clean Water Act, PL 95-218, is an amendment to the 1972 Federal Water Pollution Control Act, PL 92-500. The goal of the Clean Water Act is to make all waterways "fishable and swimmable". Section 208 requires that non-point source pollution be identified and that cumulative effects[1] be considered when planning land-use actions (Anderson et al, 1984; Geppert et al, 1984; Cobourn, 1989).

Court cases and judicial rulings have further defined the scope of natural resource management. Various rulings have specified that site specific projects as well as forest plans include an assessment of the cumulative environmental effects of the planned action (Cobourn, 1989; Anderson et al, 1984).

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[1] cumulative effects as defined here are "... the incremental impact of the action when added to other past, present, and reasonable foreseeable future actions regardless of what agency (Federal or non Federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." (40 CFR Parts 1508.7 and 1508.8, 29 November 1978).

In addition to legislative pressures to develop models for disturbance effects, society is placing an increasing value on the water resource. Whether the emphasis for this resource is clean water for domestic consumption, a thriving fishery or river recreation, there is a need to develop an understanding of the many interacting basin processes (CEARC, 1987; Brown, 1985).

Difficulties in cumulative watershed analysis often arise from the fact that many watershed basins are not under single ownership, yet the potential impacts transcend property lines. In addition, our current state of knowledge about cumulative watershed effects and how to model them is imperfect (Sidle, 1989).

In the future there will be continued pressure from the courts and the public for comprehensive land-use management, including the evaluation of large drainage basins. The 1990's will be a period of "test, validation and revision" of our understanding of the workings of natural watershed systems and of channel behavior (Cobourn, 1989).

CHANNEL RESPONSE PRINCIPLES AND CONCEPTS

Channel response and the persistence of the response within the landscape is a result of the interactions between the basin characteristics and the disturbance. These concepts are illustrated in Figure 1 and are further discussed in the following text.

BASIN CHARACTERISTICS AND PROCESSES. Fluvial systems are maintained by a source of water, sediment carried in the flowing water, and the need to dissipate energy. Hillslopes provide a source of water and sediment, while the channel provides the conduit to transport the water and the means to dissipate energy. Basin characteristics relevant to this study include the geology, soil, and related colluvial material, the stream hydraulics, and bank stability.

Sediment delivery to the channel is partially dependent on slope, geology, soil, soil moisture, and vegetation. Material from the hillslope can be delivered to the channel through processes such as mass wasting, soil creep, or overland flow. Mass wasting and soil creep is the downslope movement of soil, loose bedrock, and woody materials under the influence of gravity. Overland flow involves the movement of water and soil particles over the land surface. Hillslope sediment moves downslope on time scales varying from centuries, as in the case of soil creep, to seconds as in the case of episodic mudslides and debris avalanches (Lisle, 1984).

Sediment availability is a function of the water depth rising to access the sediment source, the ease with which the sediment can be transported, and the time elapsed since the flows last reworked the supply. Stream sediment is transported in solution, in suspension, or as bedload.

Riparian vegetation and geology will determine bank stability through the range of commonly occurring flows. Living roots help bind the soil aggregates together while the canopy shields the soil surface from raindrop impact and direct solar radiation. Riparian communities and floodplains serve as nutrient sources and sinks, filter erosional material from the hillslopes, control the water temperature, and slow water velocity by providing channel roughness.

	GENERAL MODEL		EXPLANATION
	Stream and Basin Characteristics and Processes		Integration of basin geology, mass movement potential, channel hydraulics, and vegetation.
Land-Use	Disturbance	Storms	Storm sequences and storm/land-use interactions may alter the basin and stream characteristics or processes.
	Primary Effect	HILLSLOPE RESPONSE	e.g. Changes to surface and subsurface hydrology due to heavy precipitation.
	Secondary Effect	HILLSLOPE RESPONSE	e.g. Landslides or debris flows triggered by the high pore water pressure
	Tertiary Effect	CHANNEL RESPONSE	e.g. Large quantity of sediment delivered to the channel in one incident
	Quaternary Effect	CHANNEL RESPONSE	e.g. Change in channel geometry; the channel decreases in depth and widens

Figure 1. A General Model Illustrating the Relationship Between Basin Characteristics, Disturbance, and Response

DISTURBANCE. Land-use and storm events modify basin and channel conditions. Schumm (1977) found that altering the soil characteristics, the upslope hydrology and drainage network, the vegetation, or the channel and valley sediment regime, will have an effect on the watershed energy balance.

Disturbance is a change in the characteristics or the processes within a drainage caused by natural or man-induced stress. In this discussion, disturbance refers to short-term events, e.g., storms, fire, timber harvest, or road construction, rather than those system changes that would accompany long-term disturbance events like global climate change or tectonic uplift.

The effectiveness of a storm in modifying basin and channel processes is highly dependent on the magnitude, the sequence, and the frequency of the storm events (Kochel, 1988). Storm sequences and intensity are stochastic and not easily modeled.

FLOOD EFFECTIVENESS AND CHANNEL RESPONSE. The effectiveness of a flood in producing channel change depends on the balance between resisting forces and available energy (Wolman and Miller, 1960; Wolman and Gerson, 1978; Pickup and Warner, 1976). An effective event is one with the ability to modify the landform instantaneously, transport sediment, or leave a persistent impact on the landscape.

The instantaneous modification of floodplains and channel capacity is governed by the available energy, the frequency of disturbance, the processes at work during the interval between disturbances, and the geology, vegetation, and hydraulics of the channel (Wolman and Gerson, 1978). An effective event for the modification of landform may be one that flows at or above bank-full stage (Wolman and Miller, 1960). Pickup and Warner (1976) found that in some watersheds, the modification of landform occurs with two distinct flow regimes; bank-full discharge ($Q_{1.5}$) and overtop flows.

In 1955, Lane suggested that fluvial channel adjustments were made such that water discharge times the channel slope would approximate sediment discharge times mean sediment diameter (Bradley et al, 1989).

$$Q_w s \simeq Q_s d_s$$

Where Q_w = water discharge
s = channel gradient
Q_s = sediment discharge
d_s = sediment size

Schumm (1977) proposed the following stream response models, and although no quantitative estimate of the magnitude of change can be predicted, the relationships do illustrate the expected direction of change.

$$Q_w \simeq \frac{b, d, \lambda}{s}$$

$$Q_s \simeq \frac{b, s, \lambda}{d, p}$$

Where Q_w = water discharge
b = channel width
d = channel depth
s = channel gradient
p = sinuosity
λ = meander wavelength
Q_s = sediment discharge

The movement of sediment is a measure of the work performed by a stream. The ability to do work is a function of available stream energy. Based on suspended sediment data from gravel bed systems, Wolman and Miller (1960) determined the most effective force for moving sediment is the moderate magnitude, moderate frequency event that occurs one or more days per year. Other research has found that for steep forested landscapes prone to landslide activity, the most effective event for the movement of sediment is the infrequent, high magnitude storm that occurs once or twice a century (Grant and Wolff, 1991).

Response, as used in this paper, is the change in channel features, e.g., width and depth, or streamflow because of an applied stress. Response can be defined in terms of the initial response of the channel or the long-term stability of the system through time.

Though much has been published, no common consensus has been reached among researchers and land managers regarding a conceptual approach to system and channel response (Grant and Swanson, 1992; Geppert et al, 1984; Baskerville, 1986). Review of the literature identifies four distinct response types; System Recovery, Additive or Ratchet, Amplifying or Exponential, and Thresholds. Figure 2 illustrates these response sequences.

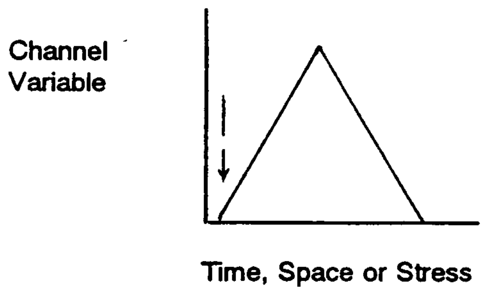
Figure 2.A illustrates a channel response which is instantaneous and short-lived. This type of response is not considered to be cumulative in nature since subsequent activities are not additive within time and space (Geppert et al, 1984).

The channel response sequence pictured in Figure 2.B results from disturbances so close in time or space that the effects of one activity are not dissipated prior to the initiation of subsequent actions. This type of response is often referred to as Additive or Ratchet (CEARC, 1987). Each disturbance over time yields the same direction and magnitude of change on the measured response variable.

Figure 2.C shows Amplifying or Exponential effects of disturbance within a system. Each additional disturbance has a greater effect due to the "priming" of the system. This response differs from additive effects (Figure 2.B) in that all activities act synergistically and do not have the same impacts (Baskerville, 1986).

The concept of a "threshold" is illustrated in Figure 2.D. Here the incremental additions of stress have little obvious consequence until a stability boundary is crossed, at which point the measured variable will change rapidly (CEARC, 1987; Schumm, 1977). Defining and predicting the point at which the specific impacts over time and

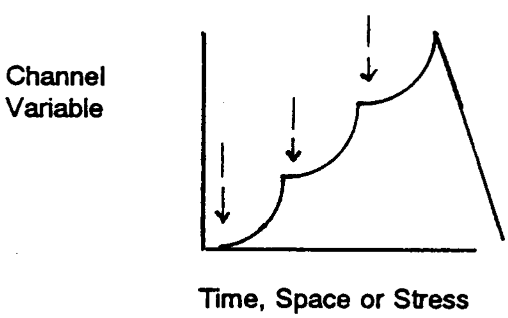
A. System Recovery



EXAMPLE

Grant & Wolff (1991), study of sediment transport in three small watersheds in the Oregon Cascades. Data from Watershed 1 shows an increase in annual sediment production after clear cutting of the unit. The unit was cut in 1966 with the largest sediment increase shown for WY1972. It is projected that post treatment sediment yields will continue to decline to pre-harvest rates by 1996.

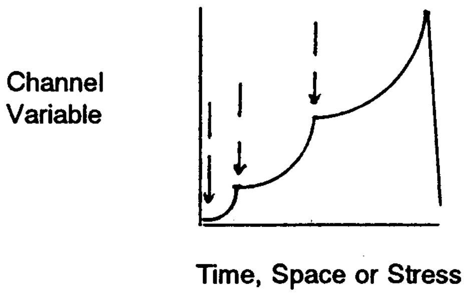
B. Additive or Ratchet



South Fork Salmon River. Sediment w/in the channel increased 350% over the 1950 pre-harvest levels as a result of land-use activities and storm events w/in the basin. The effect occurred incrementally between 1950 & 1965. Cessation of activity in 1965 reduced sediment supply and transport from the uplands. Scouring of pools further reduced sediment load in the channel (Megahan et al, 1980).

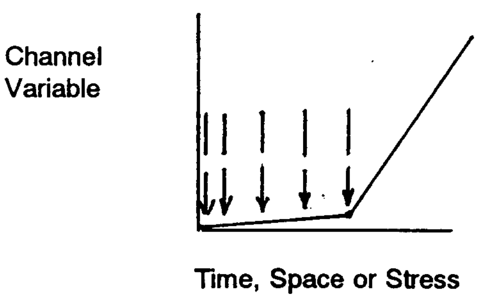
Figure 2. Four Channel Response Sequences

C. Amplifying or Exponential



Nolan & Marron (1985) describe a feedback loop between hillslope and stream processes for channels in Northern California. Bank under-cutting causes failure in hillslope colluvium. This in turn causes deflection of the thalweg, producing additional bank erosion and subsequent failures. This interaction depends on geology, soils, bank stability, and the ability of the channel to transport sediment load.

D. Threshold



The gradual steepening of a hillslope due to fluvial erosion may result in a slope that is above the angle of repose. The erosion changes the balance between the forces resisting movement (shear strength) and gravity (shear stress). Further erosion from the toe of the slope or changes in hillslope water regimes will cause failures of the slope.

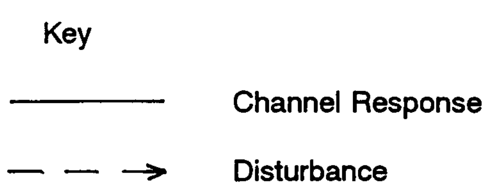


Figure 2 (cont): Four Channel Response Sequences space will cause a large shift in system behavior may not be feasible due to the complexity of interactions within natural systems and the concept of contingency (discussed in a later section).

One final geomorphic concept is the idea of the persistence of an impact on the landscape. This concept is discussed in the following section on system recovery and involves the integration of the frequency, magnitude and spatial extent of the disturbance.

CHANNEL RECOVERY AND STABILITY. Channel recovery is a measure of the persistence of an impact within the landscape. Recovery of a stream system may include the erasure of disturbance impacts, or it may be the adjustment of the channel to new discharge, sediment, and vegetative controls (dynamic equilibrium state).

The temporal and spatial scale of recovery are important considerations when evaluating system behavior. The temporal scale ranges from days to decades to centuries depending on the scope and magnitude of the original disturbance. Historic events may create a "system memory". This historic memory may not be visually apparent but may interact with basin processes and form threshold points when impacted by future disturbances.

Spatial scales range from meters to kilometers depending on the extent of the disturbance. The distance between disturbances will affect potential interactions. The evaluation of system recovery from a temporal and spatial perspective is directly tied to the use and value placed upon the resource that has been disturbed.

Stable channels are those in which the channel bed and banks exhibit resistance to increased erosion through the range of annual flow regimes (Schumm, 1977). Alluvial channels are self-formed in unconsolidated sediments transported by the river. The channel parameters, e.g., width, depth or thalweg location, continually adjust to the available energy and resisting forces (Baker, 1988). Increased flows will often cause channel widening, the formation of meander belts, and other hydraulic adjustments through which excessive energy can be dissipated and the increased water volume accommodated. Following a flood, moderate flows will rework the bedload and vegetation establishment will induce bank stability.

Bedrock dominated systems are not as flexible in their response and recovery due to the high resistance of their bed and banks to fluvial action. The ability to modify the landform or transport the dominant sediment, generally large cobbles and boulders, is attained at high flows. If there is more stream energy than can be dissipated by roughness elements and sediment transport, then macroturbulent flow, overbank flow, and damage to riparian vegetation may occur. Macroturbulent flow is capable of modifying the bedrock channels and moving exceptionally large material (Baker, 1988).

CASCADING EFFECTS AND THE CONCEPT OF CONTINGENCY. Channel response and recovery involves the interactions between basin characteristics, the disturbance, and the event effectiveness (Figure 1). The concept of cascading effects describes the movement and distribution of impacts from headwater areas to the lowlands (Grant, 1988).

An example of a cascading effect is the change in surface or subsurface flow within the soil profile which results in a mass earth movement. If the landslide delivers colluvial material into the channel, the channel may experience a change in width or depth. The change in width or depth may be separated in both time and space from the original change in pore water pressure.

As illustrated in Figure 1, there is an increase in the number of cascading effects, an increase in the spatial scale, a change in the time scale, and a decrease in the ability to interpret individual causes as one follows the direction of the arrows from the basin characteristics to the final channel response. These directional changes are due to the interactions in system variables which occur as one moves from an isolated site on the hillslope to points downstream.

Finally there is the concept of contingency (Gould, 1988). This concept is defined as the different responses that may occur if there is any alteration in a system variable or interaction. The observed responses are all probable and are dependent on the sequence of historic events.

An example of contingency may be seen in the H.J. Andrews Experimental Forest (Oregon Cascades) and the Central Oregon Coast Range paired watershed studies (Grant and Wolff, 1991; Beschta, 1978). These studies documented varying amounts of in-channel sediment transport despite the fact that the basins were of similar topography, aspect, and size. The factors which changed between the basins were the percent of area harvested, the road location and construction techniques, or the state of the basin at the time of the storm (whether the trees were standing, the trees were felled but not yarded, or the trees were yarded with post-harvest treatment having been completed).

METHODS

CASE STUDY SELECTION

To evaluate if there are any common regional patterns of channel response, I examined the case histories of six Pacific Northwest basins. The basins were chosen because they represent the range of geologic and physiographic characteristics commonly found in Northern California, Oregon, Washington, British Columbia, and Idaho (Figure 3).

Basins selected for review include (Table 1):

1. Northern California: Redwood Creek
2. Central California: San Lorenzo River
3. Idaho: South Fork (SF) Salmon River
4. Oregon Cascades: Upper Middle Fork (UMF) Willamette R.
5. Oregon Coast Range: Alsea River Tributaries; Deer Creek Flynn Creek, and Needle Branch
6. British Columbia: Carnation Creek

Stream information and the measured responses were taken from the specific studies published on each basin. Remaining background information was obtained from other published literature. The information found in each research report is a function of the intent of the original study. It is felt that data quality is good as a result of extensive peer review for most of the selected references.

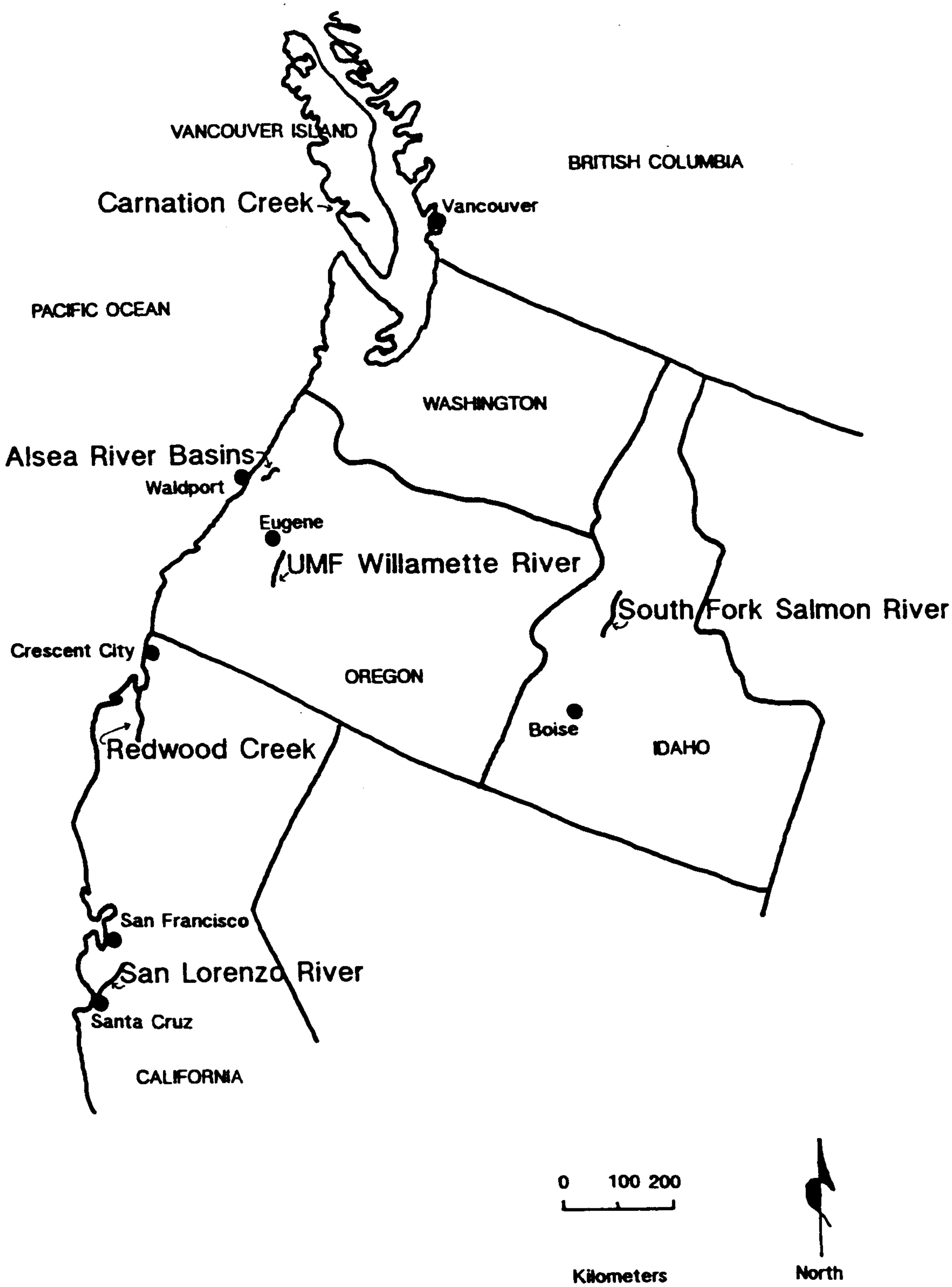


Figure 3. Location Map of the Pacific Northwest Basins Selected for this Study

Table 1. List of References Used to Construct the Data Tables and Basin Histories

San Lorenzo River, California
- Coats et al, 1985
- Nolan et al, 1984
- USGS Water Resources Data for California, 1990 WY
  - gage station: 11160500

Redwood Creek, California
- Harden et al, 1978
- Janda et al, 1975
- Lisle, 1981, 1984
- Nolan et al, 1984
- Nolan and Janda, 1978
- Hagens et al, 1986
- USGS Water Resources Data for California, 1990 WY
  - gage station: 11482500

South Fork Salmon River, Idaho
- Megahan et al, 1980
- Platts and Megahan, 1975
- US Dept of Commerce, Weather Bureau Data, 1948-1978
- USGS Water Resources Data for Idaho, 1990 WY
  - gage station: 13310700

Upper Middle Fork Willamette River, Oregon
- Harris et al, 1979
- Lyons, 1982
- Lyons and Beschta, 1983
- Portland Corps of Engineers, 1956, 1966
- Sullivan et al, 1987
- USGS Water Resources Data for Oregon, 1990 WY
  - gage station: 14144800

Carnation Creek, British Columbia
- Hetherington, 1987
- Powell, 1987
- Scrivener, 1987a, 1987b
- Environment Canada, Surface Water Data for British Columbia, 1972-1987 WY

Central Oregon Coast, Oregon
- Adams, 1979
- Beschta, 1978
- Harr et al, 1975
- O'Leary, 1980
- Paustian, 1977
- Portland Corps of Engineers, 1956, 1966
- USGS Water Resources Data for Oregon, 1990 WY
  - gage station: Flynn Creek 14306800
  - Deer Creek 14306810
  - Needle Branch 14306700

ANALYTICAL METHODS

This study investigated channel response to disturbance in relation to the principles and concepts found in the "Nature of the Problem" Chapter. Data collected fell within one of three main categories; basin characteristics and the processes delivering sediment to the channel, streamflow and bedload characteristics, and storm and land-use histories. The data are displayed in Tables 2-5, with Appendixes A-F providing a detailed discussion of each basin[2]. The information format is similar to that suggested by Kochel (1988). This allows the work from this study to be included in a larger data set from which watershed processes and relationships can be determined and verified by statistical methods.

The collected data were then analyzed with respect to stream response principles and concepts and the questions posed by this study:

1. Can channel response to disturbance be grouped according to common regional processes?
2. Do different mechanisms of water and sediment delivery to a stream produce distinct types of channel response?

LIMITATIONS OF THE STUDY

Most of the referenced studies were conducted to answer a specific question within a single basin. None were established to develop a data base for the synthesis of information on basin processes. To carve a reasonable project from this research,

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[2]Due to the variety and number of papers reviewed, the individual sources have not been broken out within Tables 2-5. The reader is referred to Table 1 and the detailed discussions found in Appendixes A-F for specific references.

the availability of consistent data and similarly measured parameters among the basins was important. No unmanaged basins were included in this study because available data is sparse and consistently measured parameters were not available.

An additional limitation of this study is the size of the sample. With only six basins, no statistical analysis was performed and some conclusions were drawn from only one example. Future studies may be better served by increasing the number of basins included, but decreasing the intensity at which each basin is evaluated.

Table 2. Basin Characteristics and Sediment Delivery Processes of the Basins

Basin	Size (km2)	Relief (meters)	Bedrock Geology [1]	Sediment Delivery Process [2]	Sediment Trigger Mechanism [3]	Recent Storm Introduced Bedload	Flood Plain Present?
San Lorenzo R, California	275	980	a	a,b	a	sand	yes
Redwood Cr, California	720	1600	b	a,b, c,e	a,b,c	sand-cobble	partial
SF Salmon R, Idaho	855	1698	c	a,d	c,d	sand	partial
UMF Willamette, Oregon	668	2165	d	a,b,c	a,b	gravel-cobble	yes
Carnation Cr, BC, Canada	10	820	d	e	b,c	gravel-sand	yes
Alsea R Basins, Oregon	2	274	a	a,b,d	a,c,d	sand-gravel	no

Notes:

1. Bedrock Geology: a) marine sandstone; b) marine greywacke and metamorphic rock; c) Intrusive rock, mostly granite; d) volcanics
2. Sediment Delivery Process: a) debris slides; b) debris avalanche; c) earthflow; d) soil creep and surface erosion; e) bank erosion
3. Sediment Trigger Mechanism: a) high pore water pressure after intense rainfall; b) slope or bank undercutting and erosion; c) loss of root strength; d) exposure of mineral soil
4. Refer to Table 1 and Appendix A-F for Data Source References

Table 3. Channel, Streamflow and Bedload Characteristics

Basin	Location[1]	Bedrock Present?	Gradient	Annual[2] Q (cms/km2)	Bankfull[2] Q (cms/km2)	Critical[3] Q (cms/km2)	Existing Bedload Material	Q1.5/ Qcrit[4]	Q1.5/ Qannual[5]
San Lorenzo R, California	Basin			0.01	0.19	0.05	coarse sand/ gravel	3.8	19
	HW	HW-yes	0.2						
	DV	DV-no	0.003						
Redwood Cr, California	Basin			0.04	0.28	0.15	gravel/ cobble	1.9	7
	HW	HW-yes	0.17						
	DV	DV-no	0.01						
SF Salmon R, Idaho	Basin	some		0.02	0.05	0.05	coarse sand	1.0	2.5
	HW		0.1						
	DV		0.04						
UMF Willamette, Oregon	Basin	some		0.03	0.15	0.44	large gravel/ cobble	0.3	5
	HW		0.07						
	DV		0.02						
Carnation Cr, BC, Canada	Basin	no		0.08	1.4	0.7	large gravel	2.0	18
	HW		0.17						
	DV		0.02						
Flynn Creek, Oregon	Basin	yes		0.06	0.56	0.72	gravel/ cobble	0.8	9
	HW		0.27						
	DV		0.03						

Notes:

1. HW-Headwater Reach; DV-Lower Mainstem Reach

2. Q: streamflow discharge from USGS and Environment Canada Stream Gaging Stations, 1990 WY
   Q1.5: bankfull discharge which occurs every 1.5 years on average (from references)
   cms/km2: a measurement of discharge, cubic meters per second per km2

3. Critical Q: streamflow discharge needed to move bedload (from references)

4. Q1.5 (Bankfull)/Qcrit: measure of the Critical Threshold (Bull, 1979)

5. Q1.5 (Bankful)/Q mean annual flow: measure of variability of stream flow

6. Refer to Table 1 and Appendix A-F for Data Source References

Table 4. Climate and Storm Characteristics of the Basins

Basin	Annual Rainfall (mm)	Storm[1] Charact	Storm Event	Storm Rainfall (mm)	Storm RI (years)	Q[2] Storm (cms/km2)	Qstorm/ Q1.5
San Lorenzo R, California	970 - 1270	a	Feb 27, 1940	346	-	2.48	13
			Dec 23, 1955	563	-	3.1	16
			Jan 3-5, 1982	467	150+	3.06	16
Redwood Cr, California	2000	b	Dec 18-27, 1955	366	50	2.03	7.3
			Dec 18-31, 1964	363	50	1.99	7.1
			Feb 28-Mar 3, 1972	165	25+	1.96	7.0
SF Salmon R, Idaho	718	b	Jun 1-21, 1964	115	-	0.12	2.4
			Jun 12-18, 1965	32	-	0.17	3.4
			Jun 9-11, 1972	29	-	0.19	3.8
			Jun 1-21, 1974	114	-	0.22	4.4
UMF Willamette Oregon	1500	b	Dec 18-31, 1964	373	100+	1.69	11
			Feb 22-Mar 6, 1972	203	-	0.65	4.3
			Jan 12-31, 1974	558	-	0.47	3.1
Carnation Cr, BC, Canada	2100 - 4800	a	Dec 1-30, 1980	603	-	2.2	1.6
			Feb 11, 1983	-	-	2	1.4
			Jan 4, 1984	-	15	2	1.4
			Feb 24,1986	-	-	2.3	1.6
Flynn Creek, Oregon	1520 - 2500	a	Jan 22-30, 1964	101	100	1.9	3.4
			Jan 5-13, 1972	220	-	1.9	3.4
			Jan 12-31, 1974	597	-	1.1	2.0
			Dec 1-7, 1975	320	-	1.2	2.1

Notes:

1. Storm Characteristics: a) primarily rain; b) rain on existing snowpack

2. Qstorm is the maximum discharge from reported storms

3. Data from US and Canadian Weather Bureau and Stream Gaging Stations

Table 5. Land-Use History and Channel Response to Disturbance

Basin	History[1]	Basin Response to Floods and Land-Use[2]	Persistence of Impact
San Lorenzo R, California	a,b,c,d	L-c,d,f	channel geometry: 1-10 yrs riparian vegetation: little impact
Redwood Cr, California	a,b,e	W-a,b,d,e,f,g	channel geometry: 5-50 yrs riparian vegetation: 100-200 yrs
SF Salmon R, Idaho	a,b	L-b,d,f	channel geometry: 0-14 yrs riparian vegetation: little impact
UMF Willamette Oregon	a,b,c	L-c,d W-a,b,e,f,g	channel geometry: 10-50 yrs riparian vegetation: 100-200 yrs
Carnation Cr, BC, Canada	a,b	L-a,b,d,g	channel geometry: 30-50 yrs riparian vegetation: 100-200 yrs (Localized)
Alsea River Basins, Oregon	a,b	L-f,g,d	channel geometry: 1-10 yrs riparian vegetation: 0-200 yrs (Localized)

Notes:

1. History: a) logging; b) road construction; c) dams; d) urbanization;
   e) National Park

2. Basin Response: a) bank instability; b) channel widening; c) channel scour;
   d) channel deposition; e) gravel bar formation; f) mass wasting in basin;
   g) riparian vegetation impacted and loss of large organic material

   W - widespread, L - localized

3. Refer to Table 1 and Appendix A-F for Data Source References

RESULTS OF THE INVESTIGATION

How do streams respond to disturbance and can these responses be grouped according to common processes? A contrast of response histories for the six selected basins will be summarized in the following subchapters: Basin Characteristics and Sediment Delivery Processes; Channel Hydraulics; and Storm and Land-Use Histories.

BASIN CHARACTERISTICS AND SEDIMENT DELIVERY PROCESSES

Table 2 is a summary of the basin characteristics and sediment delivery processes. These six basins represent the range of geologic and physiographic features found within the Pacific Northwest. They range in size from 2 km^2 (Flynn Creek, Alsea River Basin) to 855 km^2 (SF Salmon River, Idaho). The geologies range from marine sandstone to metamorphic rock to intrusive granite to volcanic (Table 2).

Sediment delivery to the channel is generally related to changes in subsurface hydrology, particularly increases in pore water pressure following high intensity rainfall or ground disturbing activities (e.g., timber harvest or road construction). The loss of root strength is also an important trigger for shallow landslides after decay of the roots begins. Landslide activity peaks within 3 years following harvest in the Oregon Coast Range, between 5-10 years in the Oregon Cascades, and between 10-20 years in the Idaho Batholith (Grant, 1992). Landslide frequency is a function of the plant rooting depth, the rate of root decay, and soil moisture. Where the soil moisture tends to be high, e.g., the Coast Range of Oregon, the rooting depth is generally shallow and decay occurs quickly resulting in peak landslide activity within 3 years of the death of the vegetation. As the soils become dryer, rooting depths generally increase and decay rates decrease resulting in longer delays between harvest activity and peak landslide occurrence.

In all basins except Carnation Creek, debris slides are the major sediment delivery process (Table 2). Debris avalanches were reported along the San Lorenzo River, Redwood Creek, the UMF Willamette River, and Deer Creek (Alsea River Basin).

Colluvium size ranges from sand to cobbles, depending on basin geology. Marine sandstones and granites tend to disintegrate into sand, while the more resistant volcanic material found in the western Cascades often reaches the channel in the form of gravel and cobbles (Table 2).

The presence or absence of a floodplain often determines if colluvial material will directly impact the channel. The San Lorenzo River, the headwaters of the SF Salmon, the UMF Willamette River, and Carnation Creek are bordered by floodplains that were noted during the original studies to have affected the channel response to storm events (Table 2).

Bank stability is a function of vegetation and bank material. Where riparian vegetation is dense or the channel bed and banks are composed of bedrock or large boulders, the bank stability is high. This occurs in the San Lorenzo River, the Alsea River Basins, the SF Salmon River, and Carnation Creek (prior to timber management activities). Bank stability was greatly reduced where landslides, debris avalanches, or land management activities damaged the riparian vegetation. Bank instability was noted along Redwood Creek, the UMF Willamette River, and Carnation Creek (Table 5).

CHANNEL HYDRAULICS

Annual and bank-full discharges were obtained from USGS stream gaging stations, WY 1990, and Environment Canada Surface Water Data Reports for British Columbia. The numbers have been reduced to show discharge per unit area so that comparison among the different sized basins would be possible. Annual streamflows[3] (Table 3) and annual rainfall (Table 4) are highest in the coastal areas of British Columbia and Oregon and decrease as one moves into Idaho or toward Central California.

The critical discharge is a measure of stream energy and the ability to transport sediment. The critical discharge is based on particle size, channel roughness, slope, and shear stress characteristics. Critical discharge values were obtained from the published research, and range from 0.05 cms/km^2 in basins with a predominant bedload of sand (sandstone and intrusive rock geologies) to 0.7 cms/km^2 where the material size is larger (Table 3).

The concept of critical thresholds was introduced by Bull (1979) as a measure of the stream energy and ability to move sediment. When the ratio of bank-full discharge to critical discharge is less than one, the bank-full flows are generally not sufficient to move the bedload, e.g., the UMF Willamette River and Flynn Creek (Alsea River Basin) (Table 3). In the San Lorenzo River, Redwood Creek, and Carnation Creek, the ratios are much greater than one. In these drainages, the bank-full flows are capable of mobilizing material from both the bed and banks.

The ratio of bank-full discharge to annual discharge illustrates the variability of flows (Table 3). When this ratio is near one, bank-full flows occur on a regular basis,

[3]cms refers to a measurement of stream discharge, cubic meters/second

either because of storm characteristics or channel geometry. For example, in the SF Salmon River, where the ratio is 2.5, bank-full flows occur frequently in association with low magnitude storms. In Carnation Creek or the San Lorenzo Basin, ratios 18 and 19 respectively, bank-full flows require larger inputs of storm waters.

In most channels, the storm introduced bedload is equal to or smaller than the existing bedload. However, in the UMF Willamette River, the introduced material was larger than the existing bedload because of the resistant geology and the occurrence of large scale slides and debris avalanches (Table 2).

STORM AND LAND-USE HISTORIES

Tables 4 and 5 illustrate the storm and land-use histories of each basin along with the observed channel responses to the recent floods. The San Lorenzo River, Carnation Creek, and Flynn Creek Basins are coastal watersheds with the predominant moisture falling as rain. In both Redwood Creek and the UMF Willamette River, the major storms have been in the form of rain-on-snow events (Table 4).

Climatic and storm data are highly variable (Table 4) (Atmospheric Environment Service, Canada; US Department of Commerce, Weather Bureau). Three or four major storms that have occurred within the last 50 years were selected as representative. Each of the basins, with the exception of Carnation Creek, has experienced a storm with recurrence interval (RI) exceeding 50 years. Recurrence interval data for the SF Salmon River were not available. Timing between the selected storms range from one year as in the SF Salmon River and Carnation Creek to over 27 years between the December 1955 and January 1982 storms in the San Lorenzo Basin.

An example of the variability in storm intensity and duration is observed in the

SF Salmon River. Here, the majority of the floods have resulted from May and June rains falling on warming snowpacks. As observed in 1965 and 1972, the precipitation amounts do not have to be large to result in peak flood events. Both of these floods were preceded by heavy winter snows and warm spring conditions. The rain accelerated snow melt and resulted in flood flows within the drainage (Table 4) (US Department of Commerce, Weather Bureau, Climatological Data for Idaho, 1948-1978 WY).

The ratio of storm discharge to bank-full discharge is a measure of the relative size of the storm flows (Tables 4). In the San Lorenzo Basin and UMF Willamette River, ratios 16 and 11 respectively, the storm flows were well above the bank-full flows. Carnation Creek, ratio 1.6, experienced storm flows very similar to the bank-full discharge.

All of the basins have a history which includes logging and road construction. Urbanization is occurring in the San Lorenzo Drainage (Table 5). Human activity, together with occasional large storms, has shaped the channel morphology observed today.

Channel response to disturbance was broken into two categories, localized and widespread (Table 5). Localized responses are responses that occur at the site of colluvium deposition or disturbance. Widespread channel responses are changes that are propagated in a downstream direction. Localized responses were observed in the San Lorenzo River basin, the SF Salmon River, the Alsea River basins, and along Carnation Creek. Redwood Creek and the UMF Willamette River experienced widespread changes in channel geometry including channel widening, aggradation of the bed, gravel bar formation, and riparian vegetation damage.

The persistence of the impact has been divided between channel geometry and riparian vegetation. Changes in channel geometry depend on the balance between erosive and constructive processes. Recovery of channel morphology parameters is generally quick, between 30 and 40 years (Table 5). In contrast, where widespread riparian damage has occurred, 100 to 200 years may be required to reestablish a functioning riparian community. Functioning riparian communities include a wide diversity of species and a mixed age class of organisms.

DISCUSSION

Evidence from the case studies and the work by Kochel (1988) suggest that four primary parameters affect how a channel will respond to disturbance. The parameters are: 1) storm sequences and storm/land-use interactions; 2) the sediment delivery process; 3) stream competence; and 4) bank stability.

STORM SEQUENCES AND STORM/LAND-USE INTERACTIONS

Storm sequences and storm/land-use interactions include the timing and spacing of disturbances within a basin (Kochel, 1988). The effects of storm sequences and the storm/land-use interaction are illustrated in the sandstone geology of the San Lorenzo River basin. In 1940, a storm with a peak discharge of 680 cms resulted in channel bed aggradation of between 0 and 0.12 meters. Fifteen years later, a storm with a peak discharge of 860 cms resulted in net scour throughout most of the basin. Nolan et al (1984) postulate that the 1940 storm depleted a large portion of the available hillslope sediment such that the later 1955 storm dissipated flow energies by scouring in-channel material. Between 1955 and 1982, there was a buildup in the hillslope sediment supply, accelerated by road construction and urbanization, which provided a sediment source for the 1982 storm. The peak discharge was measured at 842 cms and resulted in channel bed aggradation of between 0 and 0.85 meters (Nolan et al, 1984).

Research performed in the H.J. Andrews Experimental Forest in the Oregon Cascades points to the stochastic nature of storm/land-use interactions (Grant and Wolff, 1991). If a storm occurs after the trees are felled, but before yarding and post-harvest treatment (burning) is completed, limited channel response may be noted.

However, the same storm impacting the ground surface following yarding and post-harvest treatment may result in widespread sediment delivery to and transport within the channel.

Storm sequences and storm/land-use interactions may be the most difficult parameters to model but they may also be the most critical. Until it is possible to model the parameters with confidence, it will be imperative to evaluate the potential impacts of a storm at each stage of the planned management activity to take some of the surprise out of a "bad luck" situation. Adaptive management is a method that allows adjustment to occur during project implementation and will be discussed later.

SEDIMENT DELIVERY PROCESSES AND STREAM COMPETENCE

The storm discharge/bank-full discharge ratio (Table 4) indicates that the 1955 storm within the San Lorenzo Basin should have done more damage than was reported (Table 5). Flood flows were 16 times the bank-full flows. Bedrock control, the existence of a floodplain, and healthy riparian vegetation were credited with reducing channel response to the storm (Nolan et al, 1984). In the UMF Willamette River, this ratio shows the 1964 storm discharge to be 11 times greater than the bank-full flow (Table 4). This storm resulted in damage to the riparian community and channel banks due to landslide and debris avalanche activity.

Sediment movement through the channel is a function of particle size, quantity, the process of delivery, and the channel hydraulics (e.g., bed roughness, stream gradient). Introduction of fine sediment, primarily sands and small gravel, from surface erosion or overland flow without alteration of available stream power results in the rapid transport of the introduced sediment. In the SF Salmon River, once the sediment sources were stabilized, the introduced bedload was reworked and washed downstream within 14 years (Table 5) (Megahan et al, 1980).

Landslides, earthflows, and debris avalanches provide a pulse of sediment into the channel and have the most profound short and long-term impacts. When pulses of material overwhelm the sediment transport ability, the development or expansion of gravel bars, movement of the thalweg, or changes in channel cross section may occur.

Whether these responses are localized or widespread depends on the quantity and size of the bedload, the available stream power, and the bank stability. If the pulse of material is localized and the channel hydraulics and bank stability are not altered, the channel response is expected to be localized and short-lived, as seen in the San Lorenzo River (Table 5).

Within Redwood Creek, 275 slides were renewed or activated during the 1964 storm. These slides resulted in widespread channel instability. This instability results from the large quantity of colluvium overwhelming the available stream power (Harden et al, 1978). In the UMF Willamette River, it was the large size of the resistant volcanic material that resulted in channel geometry changes during the 1964 storm.

A functioning floodplain separates the channel from direct hillslope material and reduces channel impacts due to mass movement activity. This was noted in Carnation Creek where the 1984 storm activated two slides and four debris torrents on previously stable ground. Due to occurrence of wide floodplains, only one slide reached the channel (Hetherington, 1987). In contrast, much of Redwood Creek has little floodplain development with the stream banks formed by earthflows. Here colluvium is deposited directly into the channel leading to aggradation, thalweg migration, and bank instability. In additional, undercutting of the stream banks by fluvial action can reactivate earthflow movement and often introduces large slabs of material into the channel (Table 5).

Reworking of gravel, cobble or boulder bars requires flows equal to or greater than the event which developed such bars (Lisle, 1981,1984). Pickup and Warner (1976) describe three zones in alluvial channels, the in-channel area where gravel is reworked annually, the main channel, which is reworked every 30-50 years, and the higher floodplains and terraces which are reworked by catastrophic events[4]. For example, the gravel bars established during the 1964 storm along the UMF Willamette River are of such size or are sufficiently removed from the annual floods that an event equal to or greater than the 1964 flood may be required to rework the material (Lyons and Beschta, 1983).

BANK STABILITY

One last sediment source for a channel is the stream bank itself. Bank stability is largely a function of the vegetation, the soil and rock material, and the channel hydraulics (Sullivan et al, 1987). The Alsea River Basins have high bank stability due to the widespread presence of bedrock. The San Lorenzo River system, SF Salmon River, and Carnation Creek also have stable banks due to the combination of bedrock, large boulders and vegetation. Much of Redwood Creek and the UMF Willamette River have been formed in alluvial deposits. Bank stability in these channels is afforded by the presence of riparian vegetation and large organic material (Lisle, 1981,1984).

In streams where bank stability and the diversity and health of the riparian vegetation is maintained, only limited and localized channel modifications are observed. For example, the bedrock-dominated banks within the San Lorenzo Basin showed little

[4]Catastrophic floods are defined here as those having a recurrence interval exceeding 100 years.

cross-section modification as a result of high flows (Coats et al, 1985). In the UMF Willamette River debris flows during the 1964 storm damaged the floodplain vegetation resulting in widespread channel widening and braiding (Lyons and Beschta, 1983).

The following features characterize stream systems showing signs of bank instability:

1) A large quantity of sediment entering the channel in a pulse (landsliding, debris avalanches, undercutting of the toe of an earthflow) causing concentrated material deposition and deflection of flows (e.g., Redwood Creek and the UMF Willamette River).
2) Damage to the riparian community and the subsequent undercutting and sloughing of the channel banks once the vegetation is removed (e.g., Carnation Creek and Redwood Creek).
3) Movement of large organic material that may deflect the flow, which works unvegetated or unarmored reaches of the stream bank (e.g., Carnation Creek and UMF Willamette River).
4) Channels formed in alluvial deposits perpetuate bank damage in a downstream direction due to changes in the thalweg and flow hydraulics (e.g., Carnation Creek and Redwood Creek).

Work from Carnation Creek (Powell, 1987; Scrivener, 1987a) and Lisle (1981,1984) illustrate that it is damage to riparian vegetation, moss, and the associated root mass, as well as the removal of large embedded organic material that appears to initiate and propagate many changes in channel morphology. Riparian vegetation stabilizes the terrestrial-aquatic interface, with large organic material stabilizing the channel by reducing velocity and storing sediment.

The presence of moss, especially on the lower banks and bed of the channel greatly increases stability. Moss forms a mat that increases bank resistance to the abrasion of flood flows. In Carnation Creek, moss was present along the channel until anthropogenic disturbance. Once the moss mat was disturbed, bank erosion was initiated and propagated with subsequent flows. Enough material sloughed from upstream banks to affect the stability of downstream banks (Scrivener, 1987a).

Reestablishment of stable channel geometry within Redwood Creek, the UMF Willamette River, and on localized reaches along Carnation Creek and Deer Creek and Flynn Creek (Alsea River Basins) will require narrowing of the channel through accretion of bank material. Lisle (1984) found the two processes of bank accretion and vegetation establishment to reinforce each other. Both processes, however, are highly dependent on the seasonal runoff characteristics of the basin and the time between major storm events. Lisle (1984) estimates that recovery of riparian areas in Northern California from the recent storm events will require up to 100 years due to low flows in the summer and high winter peak flows (Table 5). The fluctuating water table and available stream power makes establishment of channel stabilizing moss, shrubs and conifers a slow process.

IMPLICATIONS OF THIS STUDY TO DISTURBANCE EFFECTS ANALYSIS

The prediction of channel response to disturbance entails the integration of storm sequences and storm/land-use interactions, the sediment delivery processes, the available stream power, and the stream bank stability. Interactions between basin characteristics and disturbance make it difficult to model cumulative effects and predict channel response and recovery following disturbance.

Storm sequences, storm frequencies, and storm/land-use interactions are stochastic in nature. At present, our ability to model and predict disturbance through the different sequences and frequencies of storm events and peak flows is poor. Storm and peak flow records are often non-existent or too short, especially in mountain headwater areas, to develop probability of exceedence/return interval rating curves without extrapolation of data points (Pyles, 1992). As previously stated, the characterization and prediction of storm sequences and storm/land-use interactions may prove to be the limiting factor when evaluating cumulative effects and channel response and recovery following disturbance.

Risk assessment and adaptive management are methods available to deal with the stochastic nature of large flood events and the temporal and spatial concerns of storm/land-use interactions (Tarnow, 1992). With these techniques, project goals and objectives are well defined at the onset of the planning phase. Scientific analysis is used to establish hypotheses to be tested and a monitoring system. During project implementation and monitoring, management activities can be altered (within the project goals) in order to account for unforeseen events or process interactions. Risk assessment and adaptive management acknowledge imperfect understanding of the natural system and promote learning by conducting experiments and encouraging mid-course corrections to achieve goals and objectives.

The development of a permanent data base, as suggested by Kochel (1988), is crucial to further the study of channel response to disturbance and to apply statistical methods to validate the findings. The establishment of permanent cross-sections within managed and unmanaged basins will facilitate information collection and the evaluation of trends over time.

Figure 4 was developed from the preceding analysis of stream responses to disturbance. This flow chart expands the general model found in Figure 1 to predict channel response based on storm characteristics, the sediment delivery processes, stream competence, and bank stability. After a determination of the basin characteristics, the columns may be followed down the chart to determine if a response is likely to be localized and short-lived or widespread and persistent. This chart provides a spring-board from which further analysis into the impacts of disturbance on the channel may proceed.

Most important, there must be realization and acceptance of the random nature of channel response to disturbance. While it may be possible to model the individual processes within a channel, e.g., sediment delivery or channel hydraulics, the interactive nature of basin characteristics and disturbance, as well as the concepts of contingency and cascading effects may prevent predictive modeling of entire ecosystems. This may be especially true as the size of the area under analysis or the time frame of consideration expands. Field evaluation, professional judgement, risk assessment, and adaptive management appear to be most powerful tools available in the prediction of channel response.

Storm Characteristic	Rain or Spring Runoff	Rain	Rain -on- Snow
Storm Frequency	Infrequent	Infrequent	Frequent
Sediment Delivery Process	Surface Erosion (chronic) -Fine Material -Sm Quantity	Shallow Landslide (pulse) -Fine Material -Lg Quantity	Landslide & Debris Aval (pulse) -Lg Material -Lg Quantity
Channel Hydraulics	Crit Thresh>1 $Q_{storm}/Q_{1.5}$ $\downarrow$ $Q_{1.5}/Q_{ann}$ $\downarrow$	Crit Thresh>1 $Q_{storm}/Q_{1.5}$ $\uparrow\downarrow$ $Q_{1.5}/Q_{ann}$ $\uparrow\downarrow$	Crit Thresh<1 $Q_{storm}/Q_{1.5}$ $\uparrow$ $Q_{1.5}/Q_{ann}$ $\uparrow\downarrow$
Bank Stability	High -Good Veg/LOM -Floodplain -Banks Armored	High -Good Veg/LOM -Floodplain -Banks Armored	Low -Poor Veg/LOM -No Floodplain -Alluvial river
CHANNEL RESPONSE	Local Channel Morphology Changes	Local Channel Morphology Changes	Widespread Channel Morphology & Hydraulic Changes
	Response to Storms Limited	Response to Storms Limited	Response to Storms Widespread
EXAMPLE	SF Salmon Needle Branch	Deer Creek San Lorenzo	Redwood Creek UMF Willamette

Figure 4. Pacific Northwest Channel Response Model as Suggested by this Study.

CONCLUSIONS

Is it possible to model and predict the cumulative effects and channel response due to disturbance based on the regional patterns observed from the study of six basins. The results of this study are inconclusive. Due to the lack of quantitative data (especially climate and storm recurrence intervals), the interaction between system components, the differences in basin histories, and the concept of contingency, it is not possible at this time to develop a predictive model. Process models such as Figure 4 will allow some indexing of basins and comparisons for the assessment of risk; however, professional judgement still provides the best analysis of cumulative effects and channel response and recovery following disturbance.

The evaluation of basin response and recovery patterns confirms that five parameters play key roles in how stream channels respond to a sequence of storms. These parameters are the storm sequence, the storm/land-use interactions, the processes which deliver sediment to the channel, the available stream power, and the bank stability. Of these, the storm sequence and the storm/land-use interactions have been identified as being the most difficult to model and predict.

Results from this study show that basins with low debris avalanche and earthflow potential, high stream power, and stable stream banks experience only localized and short-lived response to disturbance. On the other hand, basins with frequent debris avalanches or high earthflow potential and unstable banks experience widespread and persistent response.

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APPENDICES

APPENDIX A. SAN LORENZO RIVER, CA: DISCUSSION

Located north of Santa Cruz, California, the 355 km^2 San Lorenzo River watershed includes the drainages of Boulder, Bear, Zayante, and Bean Creeks, as well as numerous other tributaries (Figure 5).[5] The prevailing climate is mediterranean with warm summers and mild winters. Precipitation, mainly in the form of rain, falls between November and April. Mean annual precipitation fluctuates from 970 mm to 1270 mm. Snow, less than 127 mm on the average, falls on the higher peaks within the Santa Cruz Mountains (SCS, 1976; Coats et al, 1985).

The basin headwaters are located within the Santa Cruz and Ben Lomond Mountains. Elevations range from 980 meters to sea level. Coastal redwoods and Douglas fir vegetate the steep hillslopes, 30-50% slope. The geology consists of well bedded tertiary sandstone, shale, siltstone, and granite (Coats et al, 1985).

Debris avalanches and slides occur frequently. Persistent earthflows are not common. Mass movement events are triggered by increased soil water pore pressure and occur at mid and low slope locations. Bedrock controlled channels reduce the prevalence of bank undercutting at high flows. Colluvial particle size is primarily smaller than coarse sand (Nolan et al, 1984).

Stream gradients range from 0.003 to 0.2 m/m. First and second order tributaries are straight and steep with little evidence of incision into the bedrock. The lower portion of the San Lorenzo River is within an alluvial valley. Bed composition

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[5]This discussion is based on research and data from Nolan et al (1984), Coats et al (1985), The Soil Conservation Service Soil Survey for Santa Cruz County, and The USGS Water Resources Data for California, 1990 WY.

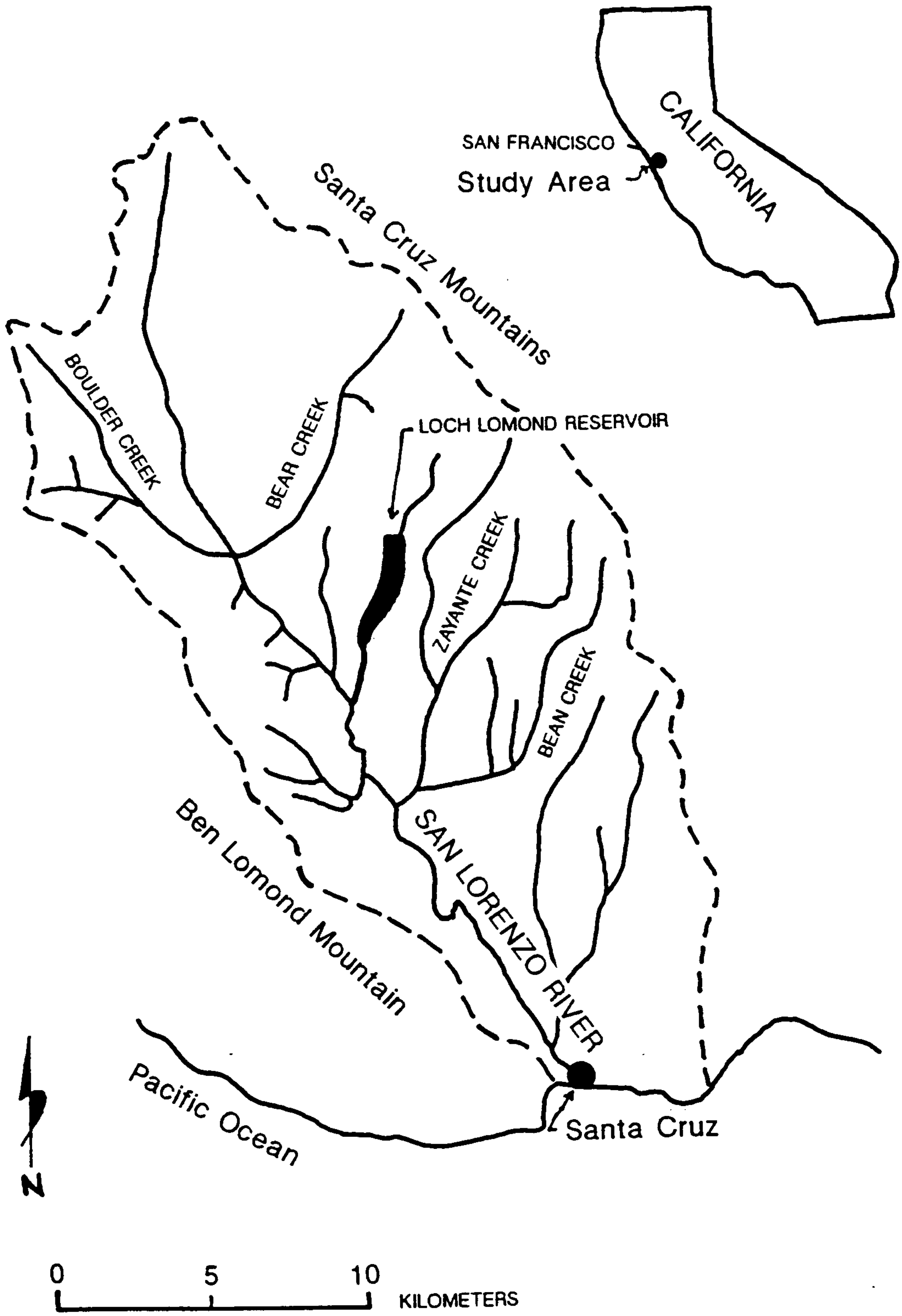

Figure A.1. Map and Location of the San Lorenzo River, CA consists of sandy alluvium and boulders surrounded by sandy alluvium (Nolan et al, 1984).

Urbanization, road construction, farming, and mining are the predominant human activities within the basin (SCS, 1976; Coats et al, 1985). Timber harvest occurred within the drainage up to the mid 1900's (Nolan et al, 1984). In 1961, Loch Lomond Reservoir was constructed upstream of the San Lorenzo River Big Trees stream gaging station, #11160500 (USGS Water Resources Data for California, 1990 WY). Storm event characteristics can be found in Table 4.

Research between 1937 and 1982 documents moderate channel response to major storms to be typical for the basin (Nolan et al, 1984). The 1940 storm resulted in bed aggradation, the 1955 storm flows resulted in channel scour. Hillslope failures that were sources of sediment during the 1940 storm did not contribute material to the channel during the 1955 storm. The duration of the flood discharge during the 1955 storm, in addition to the limited sediment supply, resulted in complete sediment transport through the system and localized scour.

The response of most channel reaches to the January 1982 storm included aggradation (between 0 and 0.85 meters), especially near obstructions, culverts, downed woody material, and at the site of mass wasting events (Nolan et al, 1984). Differences in channel response between the 1955 and 1982 storm have been associated with increased human activity and sediment availability, and the location of the high intensity precipitation cell.

The most severe channel impact during the 1982 storm was observed in Zayante and Bean Creeks where landslides resulted from locally intense rainfall and elevated soil pore pressures (Nolan et al, 1984). Coats et al (1985) report 23% of the Zayante Creek landslides to be associated with road location and failure. In other tributaries, the percent of slides associated with road corridors ranged from 0% to 66%. In the lower reaches of the San Lorenzo River, direct colluvium input to the channel was minimized due to wide floodplains (Nolan et al, 1984).

Total sediment transport, suspended and bedload, for the 1982 storm was 856,720 Mg or 3,112 Mg/km^2 (Big Trees Gage site). This load was found to be 5.9 times the annual sediment load for the area (Nolan et al, 1984).

Storm effects from the February 1940 and December 1955 storms did not persist for more than three years due to the high stream competence. By April 1982, half of the January 1982 flood related alluvium had been removed by subsequent streamflow (Coats et al, 1985; Nolan et al, 1984). Coats et al (1985) found the river basin capable of transporting large amounts of storm generated colluvium without changes to the channel geometry because of bedrock control, the lack of persistent earthflows, maintenance of bank vegetation, and the small particle size of the sediment entering the channel.

APPENDIX B. REDWOOD CREEK, CA: DISCUSSION

Located along the Northwest coast of California, Redwood Creek and adjacent tributaries form a 720 km^2 basin of fog and coastal redwoods (Figure 6).[6] The prevailing climate is mediterranean. Summers are warm with frequent fog, winters are mild and rainy. Over 2000 mm of precipitation, primarily in the form of rain, falls between October and April. Snow accumulates above 1200 meters elevation. A transient snowpack may exist between 500 meters and 1200 meters. Orographic influence predominates with rainfall differing as much as 254 mm per 305 meters elevation (Janda et al, 1975).

Elevations within the drainage range from over 1600 meters to sea level. Coastal redwoods and Douglas fir vegetate the steep hillslopes, up to 75% slope. Bedrock consists of pervasively sheared marine and metamorphic rocks known as the Franciscan assemblage. Basin geology owes its origin, metamorphism, and tectonic deformation to sea floor spreading and subduction. Tectonic uplift in the region is rapid (Janda et al, 1975).

Landslides, debris avalanches, and persistent earthflows cover approximately 30% of the basin (Janda et al, 1975). Along the 100 km length of Redwood Creek over 415 mass movement events have been observed (1978 data) (Harden et al, 1978). Eighty percent of the events occur on slopes between 30 and 70% and in areas underlain by unmetamorphosed rock of the Franciscan assemblage. Mass movement events are triggered by stream undercutting and bank erosion. Many are located near

[6] This discussion is based on research and data from Janda et al (1975), Nolan et al (1984), Harden et al (1978), Nolan and Janda (1978), USGS Water Resources Data for California, 1990 WY, Lisle (1981, 1984), and Hagens et al (1986).

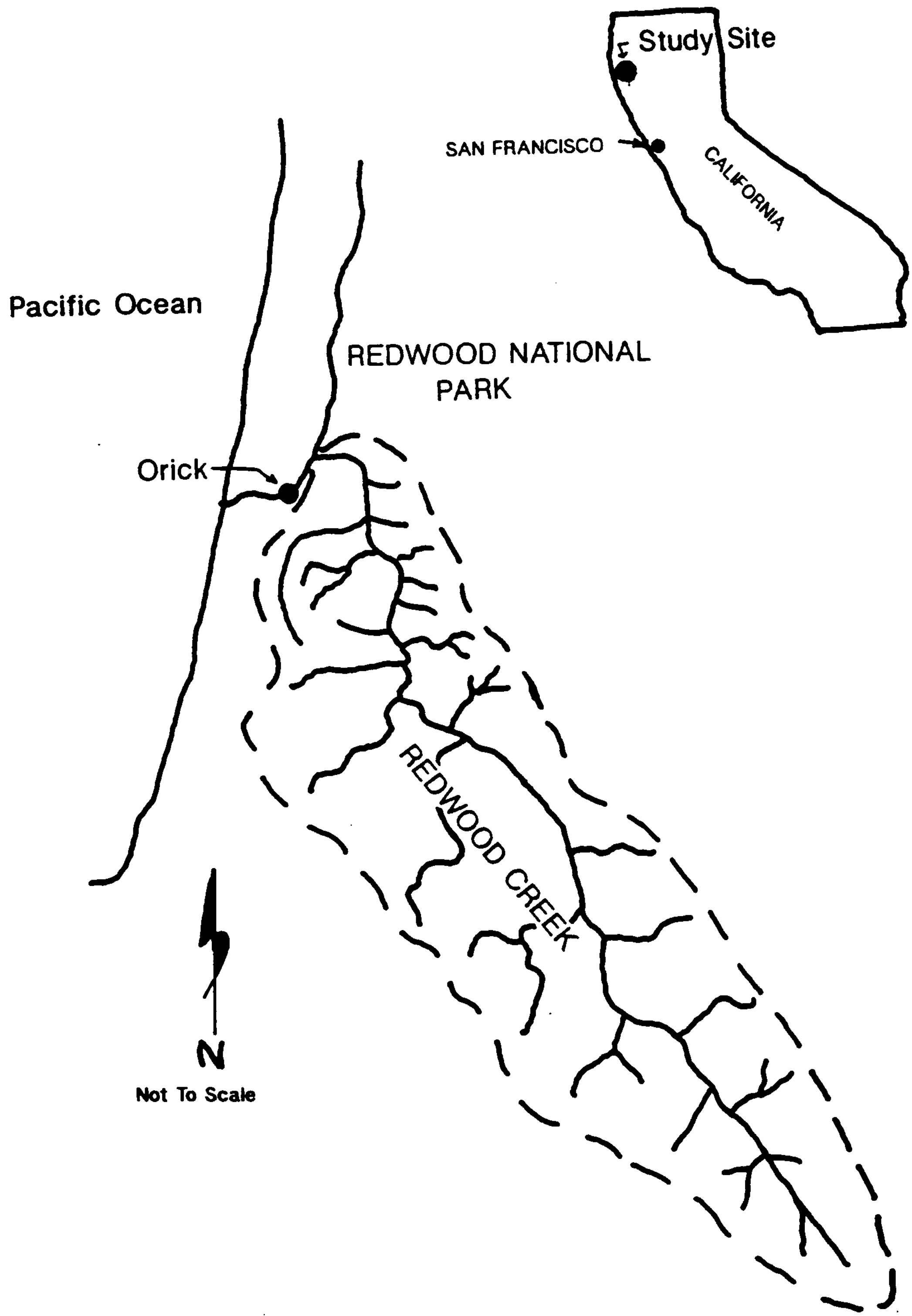

Figure A.2. Map and Location of Redwood Creek, CA roads and timber harvest units. Colluvium size is primarily coarse cobble, gravel, and sand (2 to 64 mm diameter) (Harden et al, 1978).

The first and second order tributaries are hillslope constrained and steep. Down woody debris is abundant and forms temporary sediment storage sites (Janda et al, 1975). These areas lack floodplain development, thus the channel interacts directly with the hillslopes. Sixty-four percent of these stream banks show evidence of erosion and debris slide activity. Generally dry by late summer, the channel bed is composed of cobbles and boulders. Flat topped gravel bars are common (Janda et al, 1975).

The higher order channels exhibit a braided or meandering pattern with a bed of sand and gravel. Floodplains and old channel terraces are evident (Janda et al, 1975).

The annual sediment discharge is approximately 1333 Mg/km^2, including 8 to 31% bedload (1973 to 1980 data) (Nolan et al, 1984). The sediment rate is the largest in the contiguous 48 states due in part to high annual runoff (Nolan et al, 1984).

Timber harvest within the basin began in the 1940's (Harden et al, 1978). In 1947, less than 5% of the basin had been logged with no activity occurring along Redwood Creek except clearing for pasture. Forty-seven active slides were noted.

Logging continued and was expanded to include riparian areas between 1947 and 1958 (Harden et al, 1978). As of 1978, 60% of the basin had been harvested with less than 24% of the original forest remaining intact (Nolan and Janda, 1978). Stream side harvest comprised 52% of the stream length in 1978 (Harden et al, 1978).

In 1978, 684 km of roads and 1864 km of skid trails were measured in the basin. The majority of road and skid trail construction occurred between 1955 and 1964 (Harden et al, 1978). The number of active landslides increased from 100 to 415 between 1947 and 1976, most of the increase was noted between 1962 and 1966

(Harden et al, 1978).

Climatic events in northwestern California have included a series of high intensity rainfall events followed by long periods without extreme storm events. Major floods were recorded in 1861, 1867, 1879, 1881, 1888 and 1890. A second series of storms occurred in 1950, 1953, 1955, 1960, 1964, 1966, 1970 and 1972 (Table 4) (Janda et al, 1975; Harden et al, 1978).

The storms from the late 1800's had precipitation rates, frequencies and durations similar to the more recent events (Harden et al, 1978; Janda et al, 1975). Historical accounts of the 1861 storm make no mention of streamside slides, although Harden et al (1978) noted a few slide scars on 1936 and 1947 aerial photographs. There was no evidence of channel aggradation and only limited increase in channel width associated with these storms. News reports of the 1890 storm mention landsliding associated with roads, railroads, and mine ditches (Harden et al, 1978).

Human activity in the last 25 years has likely reduced the magnitude of the storm and streamflows necessary to induce channel changes by changing the hydrologic characteristics and water routing of the hillslopes. Road construction and timber harvest adjacent to the channels have increased the availability of sediment (Harden et al, 1978; Nolan et al, 1984). Harden et al (1978) reports that the initiation or renewal of landslide activity increased as the percent of the basin in roaded and harvested condition increased.

There has been a geomorphic signature from individual storms within Redwood Creek. Basin response to recent storms includes: 1) channel aggradation and gravel berm deposition (approximately 5.2×10^6 m^3 of sediment was supplied by the 1964 storm (Hagens et al, 1986)); 2) an increase in the width of the channel; 3) an increase in the number of braided channel reaches; 4) a decrease in the size of the bed material in a downstream direction; and 5) an increase in landslide activity (the 1964 storm renewed or initiated activity in 275 slides adjacent to Redwood Creek) (Janda et al, 1975).

Recovery of the Redwood Creek depends on stabilization of hillslope and bank sediment sources, transport of the channel sediment, narrowing of the stream bed by accretion or development of channel margins, and reestablishment of streamside vegetation (Lisle, 1984). Lisle (1981) estimates the recovery of pre-storm channel geometry may take from 5 to over 30 years depending on the depth of sediment deposition. Hagens et al (1986) has estimated the residence time of stored sediment to be 25 to 100 years in the upper reaches of Redwood Creek and between 10 and 100 years for the lower end of the basin.

In the absence of large storms since 1975, vegetation has started to stabilize the bank and riparian areas. The depth of gravel accumulation and increased channel width has resulted in intergravel flows during the summer. The reduction of channel flow during the summer and high discharge during the winter has retarded the colonization of vegetation along the banks. Total recovery of the riparian areas may take between 100 and 200 years (Lisle, 1981).

APPENDIX C. SOUTH FORK SALMON RIVER, ID: DISCUSSION

The South Fork of the Salmon River drains a basin of 3,290 km^2 in central Idaho (Figure 7).[7] The climate is continental, consisting of localized, high intensity, short duration, thunderstorms during the summer and winter snow. Precipitation is 718 mm annually, of which 60% is in the form of snow (Megahan et al, 1980).

The basin headwaters are located in the Salmon River Mountains, elevation approximately 2,720 meters. The river ends at its confluence with the Salmon River, elevation 640 meters. Vegetation consists of relatively open stands of ponderosa pine and Douglas fir. Hillslopes range from 40% to over 70% and are underlain by the granites of the Idaho batholith. The soils are sandy loam to loamy sand derived from a parent material of granite saprolite (Megahan et al, 1980).

Slide activity within the basin is high due to the shallow, cohesionless soils (Megahan et al, 1980). Soil creep is common from road banks and exposed harvest areas. Loss of root cohesion following timber harvest activities contributes to the slide and soil creep frequency. Colluvium consists primarily of sand-sized material (<4.76 mm dia).

Sediment discharge has increased 350% since the advent of logging and road construction in the 1950's. Annual sediment yields are estimated to be between 1.3 m^3/km^2 and 10.0 m^3/km^2 (Megahan et al, 1980).

Logging first began in earnest in 1950. Between 1950 and 1965, 15% of the upper South Fork Salmon River basin was logged. With the logging activity came road

[7]This discussion is based on research and data by Megahan et al (1980), Platts and Megahan (1975), USGS Water Resources Data for Idaho, 1990 WY, and US Dept of Commerce, Weather Bureau Data, 1948-1978.

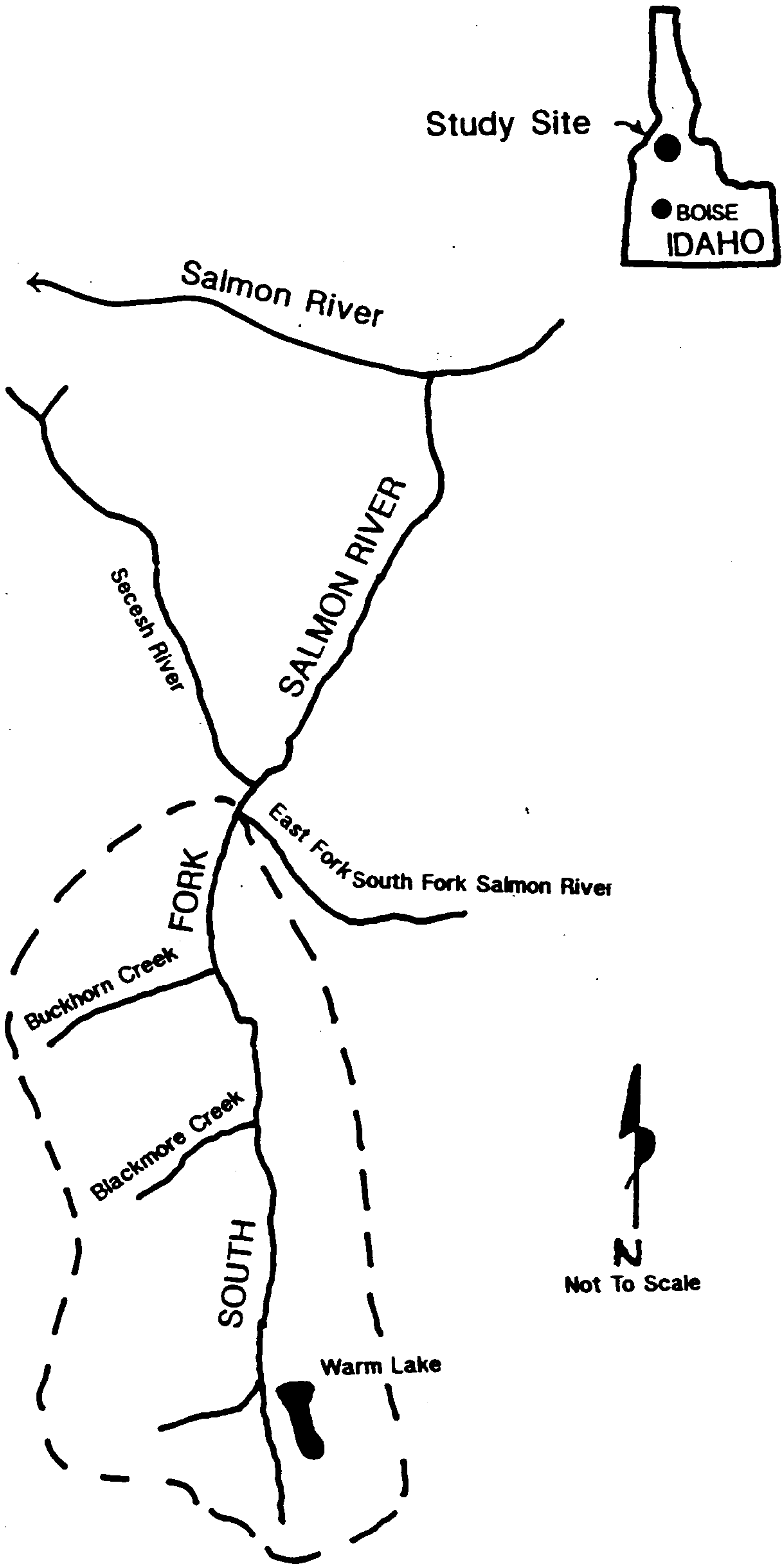

Figure A.3. Map and Location of the South Fork Salmon River, ID construction. By 1965 the upper sub-basin contained 1000 km of roads (Megahan et al, 1980). Following a review of basin resource conditions in 1964, logging was curtailed between 1965 and 1978. Limited entry was permitted starting in 1979 (Megahan et al, 1980).

Storms occurring in 1964, 1965, 1972, and 1974 are a few of the events which have helped to shape the morphology of the river basin (Table 4) (US Department of Commerce, Weather Bureau, 1948-1978). The majority of the flood events have resulted from warm May and June rains falling on "ripe" snowpacks. Thus, as observed in 1965 and 1972, the rain events themselves do not have to be large to trigger peak flood events. Both of these floods were preceded by heavy winter snows and warm spring conditions. The rain accelerated snow melt and resulted in flood flows within the drainage. Additionally, the spring storms are generally long but of low intensity. The storms of 1964 and 1974 lasted almost the entire month of June, although the average daily intensity was less than 0.13 mm/day (US Department of Commerce, Weather Bureau, Climatological Data for Idaho, 1948-1978 WY).

Channel morphology and hydraulics were not changed with the recent land-use and storm sequences. Channel widening and aggradation, as well as bank vegetation impact was limited and localized. Logging induced landslides increased the sediment supply by 350%, overwhelming the transport capacity of the river (Platts and Megahan, 1975; Megahan et al, 1980).

High flows in 1971, 1972, and 1974 (142 cms, 156 cms, and 189 cms respectively) and a reduction of hillslope sediment facilitated a decrease in bed elevation between 1966 and 1979 (0.086 meters to 0.46 meters decrease) (USGS Water Resources Data for Idaho, WY 1971-1975). Scouring in the pools reduced fines from 38% to 8% with a concurrent increase in the percent of gravel and cobbles from

12% to 29% during this same period (Megahan et al, 1980).

APPENDIX D. UPPER MIDDLE FORK WILLAMETTE RIVER, OR: DISCUSSION

Located in the western Cascades, the UMF Willamette River watershed encompasses approximately 668 km^2 of forest and river valley[8]. Buck Creek, Coal Creek, Simpson Creek, Staley Creek, and Tumblebug Creeks are a few of the major tributaries (Figure 8).

The prevailing climate is mediterranean with the majority of moisture falling between November and April. Lower elevations receive primarily rain, while snowfall is common at elevations above 1200 meters. A transient snowpack may occur between 400 and 1200 meters elevation, depending on storm and temperature characteristics (Harris et al, 1979).

The basin headwaters are located in the Oregon Cascades Recreation Area. The river flows into a water storage and flood control reservoir, Hills Creek Reservoir, prior to confluence with the North Fork of the Middle Fork of the Willamette River near Oakridge. Elevation of the drainage ranges from 260 meters near Oakridge to 2665 meters at the Cascade Crest.

Douglas Fir and red alder vegetate the steep hillslopes. Geology consists of basalt, andesite, tuff, and breccia volcanic deposits from the Little Butte Volcanic Series. Soils derived from pyroclastic and basic igneous rock, till, or colluvium are considered to be unstable (Harris et al, 1979; Lyons and Beschta, 1983).

The dominant hillslope erosional processes are mass soil movement and persistent earthflows. Lyons and Beschta (1983) found the majority of landslides and

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[8]This discussion is based on research and data by Harris et al (1979), Lyons and Beschta (1983), Sullivan et al (1987), Lyons (1982), Portland Corps of Engineers (1956, 1966), and USGS Water Resources Data for Oregon, 1990 WY.

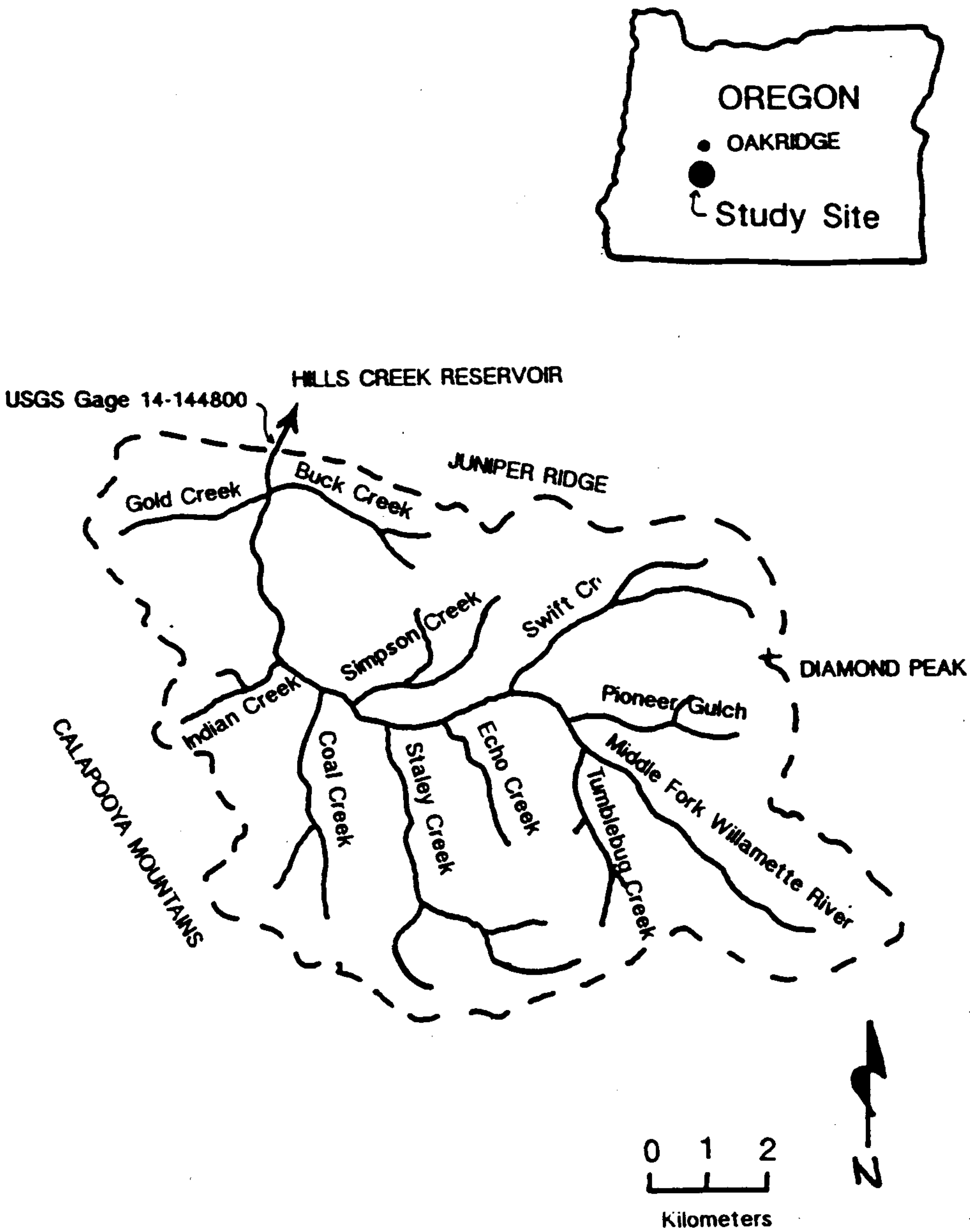

Figure A.4. Map and Location of the Upper Middle Fork Willamette River, OR debris avalanches to be associated with roads and clearcut harvest units. Lyons and Beschta (1983) report the number of new landslides occurring on 1967 photos to be 3 to 9 times greater than on previous flights. Slides occurred 27 times more frequently near roads and 23 times more frequently in harvest units (1959-1967 photo period). Road failure deposited large quantities of sediment directly into the river and its tributaries.

First and second order tributaries are straight and steep. Bed composition is primarily cobble and boulder. The mainstem consists of a wide alluvial valley with a bed of gravel and cobble (Harris et al, 1979).

The basin is primarily managed for timber production and has a mixed ownership of 90% USDA Forest Service and 10% private. Logging began in 1945. Between 1945 and 1955, approximately 1.5% of the public land had been harvested. An additional 4.5% was logged between 1955 and 1965. By 1980, 15% of the basin was harvested, primarily in the form of clearcuts (Lyons and Beschta, 1983).

The first road was built in about 1940. Between 1940 and 1965, the number of roaded hectares increased slowly. Road construction escalated after 1965, and by 1976, 7% of the area was in roads (Lyons and Beschta, 1983).

This portion of the western Cascades is typified by channels which exhibit quick flow response to precipitation. Major storm and flood events have occurred in 1964, 1972, and 1974 (Table 4) (US Dept of Commerce, Weather Bureau, 1948-1978; Portland District Corps of Engineers, 1956, 1966).

Data collected between 1936 and 1980 indicate widespread channel response to the 1964 storm event. In the mainstem, stream bed aggradation and the formation of large gravel bars occurred at major tributary junctions. Many tributaries incurred bed scour due to the large volume of sediment moving through the system (Lyons and

Beschta, 1983).

An increase in channel width, between 25 and 250%, was found in all but 8 km of the stream between 1959 and 1967. This increase was associated with channel bed aggradation and the destruction of riparian vegetation as large woody debris was transported over the floodplain, uprooting and toppling vegetation (Lyons and Beschta, 1983). Since 1972, there has been a gradual trend in decreased channel width due to vegetation reestablishment. Seventeen of 25 survey sections illustrate this trend, with a significant decrease in width identified in seven segments (Lyons and Beschta, 1983). A shift in stream channel vegetation from conifer to willow and alder has been noted since the 1964 flood (Sullivan et al, 1987).

The UMF Willamette River response to recent storm events was due to an increase in sediment availability and the large size of the colluvium introduced by debris slides and avalanches (Lyons and Beschta, 1983). Estimated time of channel recovery, for example, width and depth, is between 10 and 50 years. The recovery of riparian vegetation is estimated between 100 and 200 years (Sullivan et al, 1987).

APPENDIX E. CARNATION CREEK, BRITISH COLUMBIA: DISCUSSION

Carnation Creek drains a basin of 10 km^2 on Vancouver Island, British Columbia, Canada (Figure 9).[9] The climate is mediterranean with rainy, mild winters and dry, warm summers. Annual precipitation averages 3500 mm, with strong orographic effects as one moves inland (Scrivener, 1987a).

The headwaters are located in the Pelham Range at an elevation of 820 meters. The river flows westward to Barkley Sound. Vegetation consists of western red cedar, Sitka spruce, and western hemlock. Steep, glaciated hillslopes are underlain by volcanic bedrock. The soils are shallow, coarse and high in organic matter. Preharvest bank stability is high due to moss, living root cohesion and soil structure (Scrivener, 1987a). In its natural state, limited surface erosion or landslide activity has been noted (Hetherington, 1987).

Headwater tributaries have bedrock and boulder beds with gradients between 16 and 49% (Scrivener, 1987a). The lower end of the basin is characterized by a gradient of 1.9% and extensive gravel bars. Bed material is sand and gravel, less than 100 mm in diameter. Down woody material is common and floodplains are developed along most of the channel reaches (Scrivener, 1987a).

The first harvest in the basin occurred in 1976. Forty-one percent of the basin was harvested over a six year period. Thirteen cutblocks were winter logged using "highlead systems". Full bench road construction took place on ridgetops (Scrivener, 1987a).

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[9]This discussion is based on research and data by Powell (1987), Scrivener (1987a,b), Hetherington (1987), and Surface Water and Atmospheric observations for British Columbia, 1972-1987.

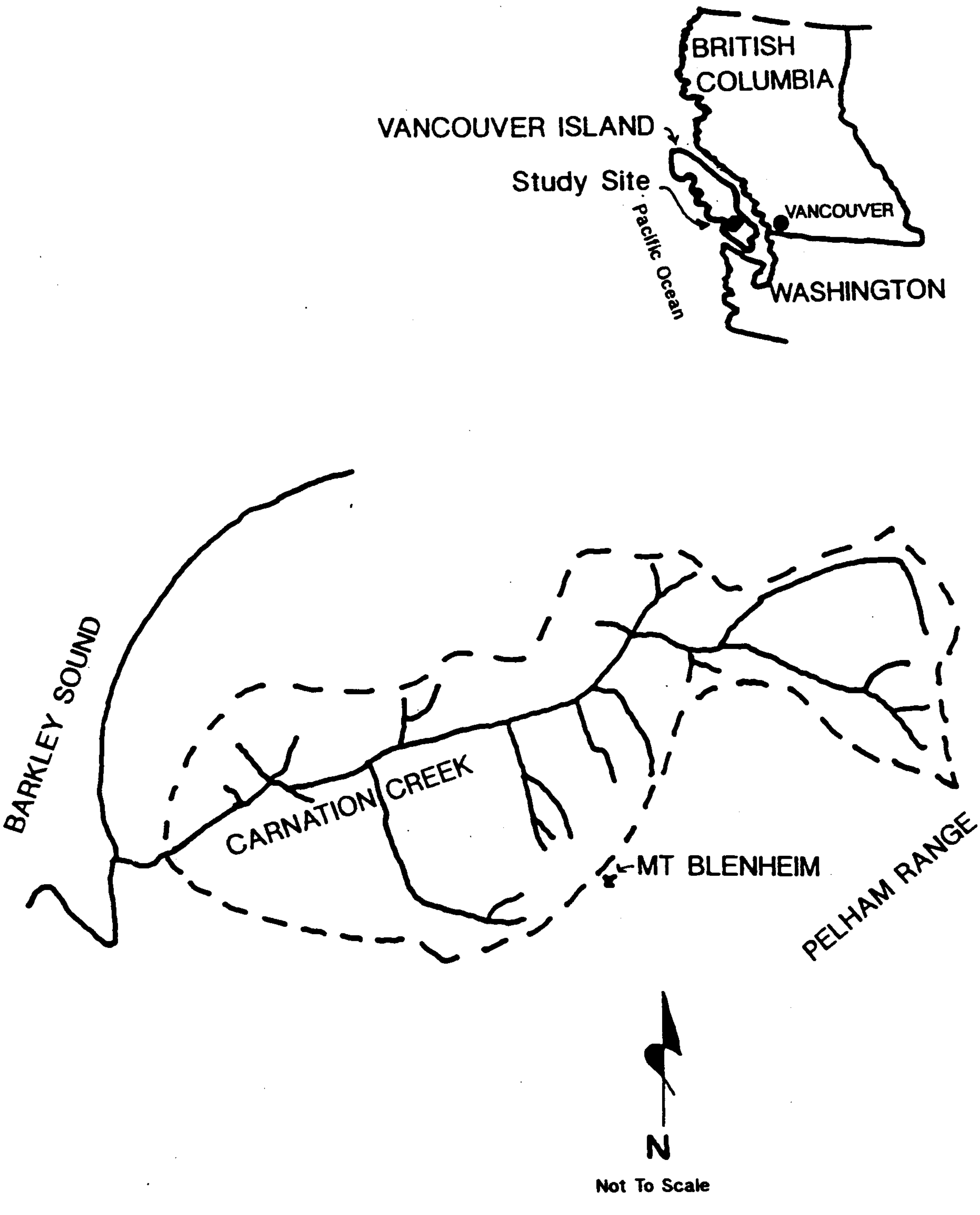

Figure A.5. Map and Location of Carnation Creek, BC

Researchers initiated and monitored three streamside management zones during harvest activities; undisturbed, intense treatment, and careful treatment. The management zones were of variable width. Deciduous vegetation and merchantable trees were left along the banks in the undisturbed streamside treatment. Both the intense treatment and the careful streamside treatment included the removal of merchantable trees and the girdling and cutting of streamside alder. Because of harvest and yarding activities, stream banks were heavily damaged within the intense treatment area (Scrivener, 1987a).

Storm response is flashy with streamflow generated by the subsurface flow of water through shallow soils and direct precipitation on the channel. Major storms have occurred in 1980, 1983, 1984, 1986 (Table 4). Most of the storms are of long duration with the maximum 24 hour precipitation being recorded the day of or the day before the flood (Atmospheric Environment Service, WY 1974-1986).

Changes in channel morphology, e.g., width and depth, were observed in all three streamside management areas following the storms. Within the undisturbed area, changes to the channel included some widening and deepening. Salvage logging was conducted to remove blowdown and resulted in some lateral adjustment of the channel and thalweg straightening. However, the rate of change was similar to preharvest rates and the channel is considered stable (Powell, 1987).

Channel widening, thalweg straightening, and changes in pool configuration were noted in both the intensive management and careful management zones. In treatment areas, bank erosion is 2.7 times that of the undisturbed areas. Since 1976, pea gravel and sand has increased 4.6% to 5.8% within and below areas of intense streamside harvest (Scrivener, 1987b). Most changes in channel structure and gravel quality occurred two to five years following harvest. The rate of change increased from preharvest trends and the channel reach is considered to be unstable (Powell, 1987).

Channel response to disturbance was due to increased sediment availability as a result of bank erosion and the loss of roughness elements. The January 1984 storm activated two small slides and four debris torrents in previously stable ground. Most of the slide and debris torrent material was deposited on the floodplain (Hetherington, 1987).

APPENDIX F. ALSEA RIVER BASINS, OR: DISCUSSION

The Alsea River watersheds of Flynn Creek, Deer Creek and Needle Branch of Drift Creek were used to describe the response of Central Oregon Coast Range basins to disturbance (Figure 10).[10] The climate is mediterranean with mild, wet winters and warm, dry summers. The Coast Range receives between 1520 and 2500 mm of rain. The orographic effect of increased precipitation with an increase in elevation is pronounced (Beschta, 1978).

Slide activity within the central coast is high due to shallow, cohesionless soils. Adams (1979) found mass movement accounts for 55% of the sediment delivered to the channel. Surface erosion and stream bank failure accounts for 20% and 25% respectively. Colluvium is primarily sandstone sand, gravel and cobbles.

Eighty percent of the channel is bedrock controlled, especially in the 1st and 2nd order tributaries. Coarse sediment is stored behind obstructions. In the mainstem, a gravel and cobble bed predominates (Paustian, 1977). Stream banks are stable due to vegetation and root strength (Paustian, 1977).

Stream response to precipitation is rapid. Average daily discharge ranges from 0.046 cms in Needle Branch to 0.18 cms within Deer Creek, USGS gaging stations # 14306700 and #14306810, respectively (USGS Water Resources Data for Oregon, 1990 WY).

Sediment discharge, prior to road construction and harvest, within Needle Branch and Deer Creek was found to be 53 tons/km^2 and 97 tons/km^2, respectively.

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[10]This discussion is based on research and data by Beschta (1978), Harr et al, (1975), Paustian (1977), Adams (1979), O'Leary (1980), and Portland District Corps of Engineers (1956, 1966).

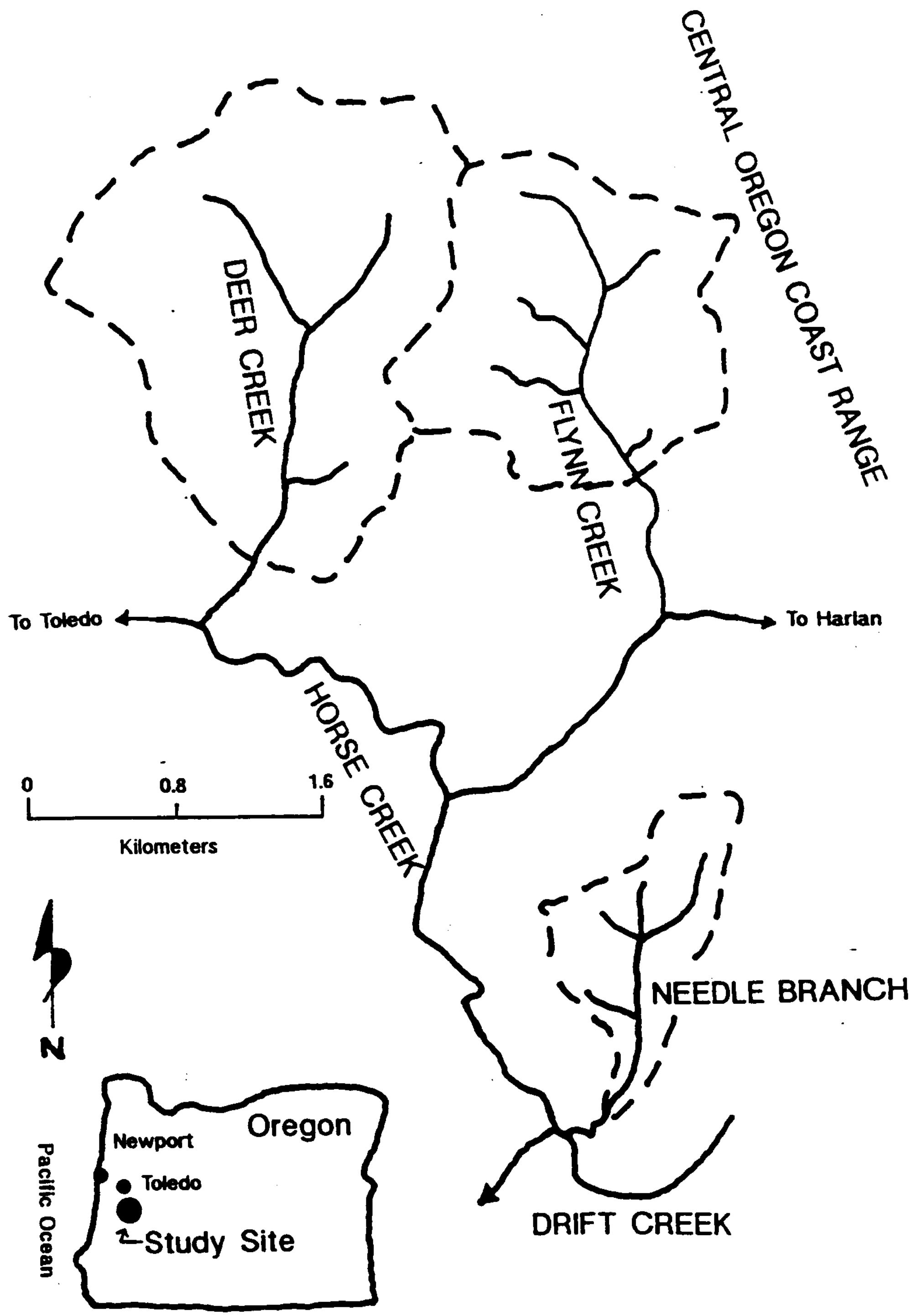

Figure A.6. Map and Location of the Alsea Watersheds, Central Oregon Coast Range

The suspended sediment yields in Flynn Creek ranged from 18 to 433 tons/km^2 and averaged 98 tons/km^2 (Beschta, 1978). O'Leary (1980) calculated the critical discharge within Flynn Creek to be 0.72 cms/km^2. Bedload is primarily sand and gravel.

Over the centuries, the Coast Range has been disturbed by fire, floods and human activity. In the late 1800's, the Nestucca and Yaquina fires burned much of the area. Splash dam logging in the late 1800's, clearcut timber harvests from 1950 to present, and stream cleaning of large organic debris in the 1960's have had an impact on basin morphology and stream response to storm events.

The Alsea watershed study was a paired watershed experiment which ran between 1958 and 1973 (Beschta, 1978). Flynn Creek, 2.02 km^2, was used as a control basin with no timber harvest or road building.

Deer Creek, 3.03 km^2, was roaded in 1965 and 25% of the basin harvested in patch cuts in 1966. The basin contains 6 km of roads. Post treatment prescriptions included a light burn of slash in the lower unit. The two upper units were not burned. A stream buffer extending 15 to 30 meters was maintained.

Needle Branch, 0.70 km^2, was roaded in 1965 and 82% of the basin clearcut in 1966. The basin contains 2.4 km of roads. Post harvest slash burns were severe and resulted in exposed mineral soil (Beschta, 1978). No buffer strip was maintained adjacent to the stream.

Severe storms have initiated flood events throughout recorded history, Table 4 (US Department of Commerce, Weather Bureau, 1948-1978). The return period for the December 1964-January 1965 storm is estimated at 100 years. Frozen ground and snow in the higher elevations combined with a warm rain to induce flooding. Deer Creek crested on January 28 with a peak flow of 5.69 cms. Flynn Creek crested with a peak flow of 3.9 cms (Portland District Corps of Engineers, 1966).

Following the 1964 storm, road and landing related failures within the Deer Creek drainage accounted for the deposition of colluvium into the channel through debris avalanches. Annual sediment yields within Deer Creek increased from 97 tons/km^2 to 136 tons/km^2 (Beschta, 1978). A drop to preharvest sediment levels was observed by 1968. In 1972, the suspended sediment level again increased due to several road related slope failures during the January 11, 1972 storm. Return to preharvest sediment levels was noted within two years (Beschta, 1978).

Needle Branch did not exhibit the road and landing related debris avalanches that occurred on Deer Creek. Instead, the lack of stream buffer and a severe slash burn resulted in surface erosion. The sediment rate showed an initial increase in 1967, from 53 tons/km^2 to 146 tons/km^2, with a gradual decline to near preharvest levels by 1972 (Beschta, 1978).

Few channel morphology changes were described within the original studies. Recovery of sediment levels to preharvest status is the result of stream competence to move the material coupled with relatively modest supply rates.