Proceedings of the Pacific Northwest Floods of February 1996 Water Issues Conference
October 7-8, 1996 -- Portland, OR

2330

LESSONS FROM A FLOOD: AN INTEGRATED VIEW OF THE FEBRUARY 1996 FLOOD IN THE MCKENZIE RIVER BASIN

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INTRODUCTION

The storm of February 1996 provides important opportunities to examine the effects of natural conditions (e.g., topography, soil) and land use on watershed response to major storm events. Landscape susceptibility, as a function of geology, topography and vegetation, can lead to variable responses of hillslopes and stream channels to floods (Figure 1). We believe that the key to understanding hillslope and channel responses to floods is to take an integrated, watershed-scale view. In particular, we are interested in understanding how disturbances propagated through the landscape, from hillslopes to small to large channels, and the factors that suppressed or augmented these disturbance cascades. Despite studies of the effects of past storms, there is much to learn from the 1996 event; specifically how debris slides, debris flows, road networks, stream channels, riparian vegetation and valley floors interacted during the flood to produce the pattern and magnitude of flood disturbances observed.

The objectives of this research are to:

- Describe linkages of disturbances, including debris slides, debris flows, road failures, sediment and woody debris movement, in contributing to downstream channel, valley floor, and riparian changes;
- Examine these processes over a range of topographic, geologic, land use, and climatic settings;
- Determine how prior conditions on hillslopes and channels influenced the rate, magnitude, and timing of water, sediment, and large woody debris movement at the watershed scale. Comparison of the effects of the 1996 flood with landscape responses to previous large floods, notably the 1964-65 events, will contribute to this historical perspective.

The upper Blue River watershed, which contains the H.J. Andrews Experimental Forest, and additional adjacent watersheds of the McKenzie River were selected as the focus of these studies. Extensive pre-flood hydrologic, geomorphic and ecologic data exist for the Lookout Creek basin (62 km2) and portions of the upper Blue River watershed (119 km2). These areas included a wide range of flood effects and also represent differing land use histories. During the 1950s and 1960s, approximately 20% of Lookout Creek watershed was clearcut and roaded, but little logging has occurred since. Blue River watershed has had similar amounts of clearcutting and road construction, but these have occurred more recently (Jones and Grant, 1996). Here we describe the research components of our study and some very preliminary findings from this on-going work.

BACKGROUND AND FLOOD DYNAMICS

The pattern of runoff, which varied with elevation, was strongly controlled by the interaction of snowpack dynamics with incoming precipitation as documented in small, gaged watersheds in the H.J. Andrews Experimental Forest. The amount of water stored in the snowpack was a primary factor influencing the relative size and timing of peak flows throughout the landscape. Three distinct elevational responses were present: a lower zone extending from approximately 400-800 m where melting from a relatively thin, wet snowpack directly augmented high precipitation intensities; a middle zone from 800-1200 m where a deeper snowpack first stored then released water; and an upper zone above 1200 m where a very deep snowpack stored much of the direct precipitation and buffered the storm intensity. More details of the storm and stream gage values can be found at http://www.fsl.orst.edu/lter/flood/floodrpt.htm. Overall, the February 1996 storm appears to have had greater streamflows at lower elevations and smaller flows at higher elevations than the December 1964 flood. However, streamflow and discharge estimates from extreme events potentially have very large errors.

STUDY COMPONENTS

Mass movements

The objectives of this sub-component were to inventory debris slides and debris flows that occurred as a result of the February 1996 storm and to determine the patterns of control by natural factors (e.g., topography, soil) and influences of land use practices. We view mass movements as operating in a cascade of processes in which debris slides from hillslopes can be transformed into debris flows, collecting additional sediment and woody debris as they move down steep, low-order channels, then possibly entering fourth- and fifth-order streams. Earlier inventories of mass movements and their relation to geology, soil, climate, topography, and land use (Swanson and Dyrness, 1975; Marion, 1981; Ice, 1985) set the stage for examining effects of changing watershed conditions on storm response - past, present, and future.

We are interested in the following questions:

- What are the relative rates of the occurrence of mass movements in terrains of differing land use and geophysical properties?
- How do the types of slides and their runout characteristics vary among terrains with differing geophysical properties and land uses?
- What are the relative effects of various natural and management-related factors that influence slide and debris flow frequency?
- What is the relative significance of factors controlling the runout of debris slides and flows?

Methods

The inventories include debris slides (shallow, rapid soil movement down hillslopes) and debris flows (rapid movements of soil, alluvium, and organic debris down stream channels) that occurred in the Blue River basin, which includes Lookout Creek and the H.J. Andrews Experimental Forest. Features as small as 10 yds3 (7.5 m3) were inventoried, but for comparison with earlier inventories (Swanson and Dyrness, 1975; Marion 1981), a minimum volume of 100 yds3 (75m3) was used. Sites where mass movements had occurred were located through ground searches of the full road network, by walking stream channels of fourth-order and larger and by following all debris flow tracks. The watersheds were also observed from vantage points along roads, aerial reconnaissance in fixed wing aircraft and helicopter, and using 1:12,000 post-flood aerial photographs. Possible sites of mass movement were inspected on the ground. A subsample of first- through third-order channels and mouths of their tributaries were also field surveyed. The detection of mass movements was done by using aerial photographs with field inspection where intensive field sampling was conducted to determine the limits of slide detection in areas where only photo techniques might be employed.

It is felt that this sampling approach yields a thorough inventory of events that run out into higher order channels or that have occurred in plantations or road right-of-ways. An estimate of the total number of events reaching first- through third-order streams can be calculated from the subsample. The sample of events that did not reach channels is incomplete and we lack a strong basis for estimating this population of events. However, mass movements with longest runout may have the greatest impact on roads, streams and other resources.

We are particularly interested in mechanisms contributing to mass movement initiation, runout, and stopping. Key observations included land use, forest condition, topographic and geomorphic setting (e.g., earthflow toe, streamside where bank cutting could be a factor, channel head, planar slope, etc.), and measurements and characterization of the slide itself.

Results

Recent mass movements following the February flood within the Blue River watershed were compared with an earlier intensive inventory of debris slides and flows (Swanson and Dyrness 1975; Marion 1981). Hydrologic and geologic factors are the primary controls of the spatial distribution of mass movements. A total of 36 debris slides larger than 75 m3 were observed following the 1996 event in the H.J. Andrews Experimental Forest, compared with 72 in the same area following the 1964 flood. While a similar number of slides initiated in natural, post-wild fire forests during the two flood events (15 in 1964, 16 in 1996), there were very different numbers of slides initiated in post-clearcut plantations (17 in 1964, 3 in 1996) and related to roads (40 in 1964, 17 in 1996). These differences reflect the distinctive land use history of the Lookout Creek watershed. Road construction and forest-cutting activity were high beginning in 1950 and leading up to the 1964 event, but little road building or forest harvest occurred between 1970 and 1996. All three slides in plantations began in cutting units less than 20 years old, suggesting a reduction of slide potential as a result of several possible mechanisms, including previous failure of marginally stable sites, recovery of root strength and other factors. Road-related slide rates appear to have decreased, but pre-1964 roads continue to experience mass movements. In the total study area, the highest rate of sliding in plantations was in clearcuts less than 20 yrs old.

Of additional interest is the runout of slides into stream channels and the ability of mass movements to trigger debris flows down small channels and to deliver sediment and woody debris to larger streams. Of the 36 slides in 1996, 16 resulted in debris flows down 8 separate channels.

Of these, only 3 first- to third- order channels delivered debris flows into higher-order channels in the Lookout Creek watershed. Substantial modification of channels and riparian vegetation occurred as a result of these flows in these sites.

Road network interaction with flood processes

Forest road networks may interact with flood processes in many ways. Roads have been implicated in numerous studies of landslides for having the highest unit-area slide rates during storms, typically 10 to 100 times greater than forested rates (Swanson and Dyrness, 1975; Swanson et al., 1981; Ice, 1985). Many debris flows initiate as road prism or stream-crossing failures; roads may also contribute to landslides below roads by diverting surface drainage onto marginally stable slopes. Partial or complete damming of culverts followed by ponding and failure of the road prism has been noted as a major mechanism contributing to debris flow initiation. Recent work (Wemple, 1994; Jones and Grant, 1996; Wemple et al., 1996) suggests that roads may also play a significant role in extending the drainage network during storms, as roadside ditches or the roads themselves intercept precipitation, snowmelt, and cutbank subsurface flow. These flows are then rapidly diverted to channels, or initiate gullies that connect ditch drainages with natural streams. Increased peak flows and delivery of bedload to streams may accompany gully initiation due to road drainage effects. We observed many of these flow paths during the 1996 flood at the H.J. Andrews Forest. Roads and road crossings were often factors in complex sequences of events involving landslides, debris flow initiation, and stream diversions.

To examine how road networks interacted with the flood, we ask:

- What were the dominant road drainage problems during the flood (e.g., hydraulic undersizing, bedload or debris flows plugging culverts), and how were these problems distributed with respect to road position (i.e., valley floor, midslope, and ridgetop), road age, culvert size, and hillslope topography (convergent, divergent, planar slopes)?
- What role did roads play in sequences of events involving mass movements, culvert failures, stream diversions, and gully initiation?
- What factors contributed to road 'successes' during the flood, i.e., where did road failures not occur and why?

Methods

We investigated how the forest road network interacted with water and sediment transport during the flood through a detailed inventory of road damage and failures in the Blue River and Lookout Creek drainages. We have: 1) evaluated the specific pattern of flood-related impacts to the road network by examining fluvial and mass movement disturbances associated with the roads; 2) investigated physical controls that increase susceptibility to failure; and 3) studied interaction of the road network with hillslope and channel processes. Two independent surveys were conducted to evaluate the extent of road-related flood effects. First, a basin survey of all accessible roads (350 km) within the study area was conducted to inventory fluvial and mass-movement events associated with the roads. Second, a transect survey based on a stratified sampling design was implemented in order to evaluate culvert performance. While the basin inventory allowed for a quick assessment of the percentage of the road network affected by the flood and the degree of patchiness in the distribution of flood impacts, the transect survey allowed us to define road-related effects more precisely.

Basin Inventory: The extensive survey focused on an examination of fluvial and mass movement processes associated with the road network. We characterized eight types of failure mechanisms involving both mass-movements (debris flows, fillslope failures, hillslope slides, cutslope failures and slumping) and fluvial events (excess bedload, hillslope gullying, and ditch incision).

Transect Survey: To evaluate the frequency of road drainage failures, we examined a series of 2-km road transects distributed throughout the two basins. These transects were originally selected by Wemple (1994) and Wemple et al. (1996) based on a stratification of Lookout Creek (119 km total road length) and Blue River (230 km total road length) roads by decade of construction (1950's and prior, 1960's, 1970's and 1980's) and hillslope position (ridge or upper hillslope, midslopes and valley floor). Thirty-one 2-km road transects (approximately 20% of the total road length in the two basins) were surveyed for this study. The road transect survey included all mass movement and fluvial events mapped in the basin inventory, as well as culvert failure and road drainage problems.

Results

On average, 12% of stream-crossing culverts and 11% of ditch-relief culverts experienced partial or complete failure due to either complete removal by debris flows or plugging by sediment and organic material. The distribution of culvert failure was highly variable in space. In the 31 2-km transects surveyed, as many as 50% and as few as 0% of culverts failed to pass water and sediment during the flood.

A variety of fluvial and mass wasting disturbances were associated with the road network. Fillslope failures were the most prevalent mass movement events associated with roads and were responsible for the greatest volume of material removed from the road prism. Plugging of stream-crossing culverts by bedload and gullying of road surfaces and hillslopes by concentrated surface runoff were the dominant forms of fluvial disturbance occurring on the road network. Debris flows and hillslope slides initiated above roads and moved substantial volumes of sediment onto the road prism, often resulting in continuation of mass movements or initiation of fluvial disturbances (gullying, ditch incision) within the road right-of-way.

The position of a road within a landscape is a major determinant of the extent of road-related flood impacts. Roads located on ridges were largely unaffected by debris flows and landslides from upslope and were minor contributors to sediment moved downslope in the form of fillslope slides. Midslope roads were frequently intersected by landslides and debris flows, resulting in partial trapping of material and frequent transitions to other mass movement or fluvial processes. Fillslope failures initiated most frequently from midslope roads, providing substantial sources of sediment to hillslopes and channels. Roads located on valley floors commonly trapped debris flows or experienced fluvial disturbance.

Flood effects on channels, valley floors and riparian vegetation

In this sub-component, we seek to develop causal relationships among flood processes, changes to channels, valley floors, riparian zones and management activities. Our conceptual framework for interpreting results of the stream channel study is based upon the premise that three primary agents were responsible for channel and riparian change: 1) high discharge; 2) transport of coarse sediment; and 3) transport of large woody debris. Stream systems experienced different degrees of each of these, acting individually or in combination. For example, some systems had high streamflow with little sediment and wood transport, while others experienced high levels of all three. We hypothesize that differences in the responses of stream channels to the flood can be interpreted in terms of the relative abundance and transport rate of wood and sediment (either pre-existing in the channel or supplied during the event through various processes) and by the channel and valley floor geometry, particularly the degree to which the channel is constrained by resistant margins (i.e., bedrock or high terraces). This study allows us to test these hypotheses across a range of water, wood, sediment, and channel conditions. Management activities may have influenced the response of channels primarily by affecting the relative abundance or supply rate of water, sediment, and wood. This may have occurred: 1) through practices that increased the frequency of mass movements from hillslopes; 2) through practices (i.e., salvage, silviculture, instream structures) that changed the level of woody debris loading in small or large channels; and 3) through direct interaction of features (roads, bridges, riparian vegetation) in augmenting or suppressing delivery of material.

Key questions we are examining include:

- What was the extent and magnitude of flood effects to channels in a sample of adjacent basins? How might basin scale controls, including geology, topography, and land use explain this variation?
- What was the relative importance of mass movements, high streamflows, channel morphology, sources of sediment and large woody debris as primary drivers and determinants of channel and riparian disturbance?
- What effect did this flood have on channel morphology, including pattern, distribution, and abundance of channel and valley floor units and alluvial surfaces?
- How did flood impact zones during the 1996 flood compare with their location during the 1964-65 floods? Was the extent of riparian disturbance similar for the two events, as evidenced by age and type of riparian vegetation affected?
- What role did management activities play in channel disturbances, including: effects on mass movement initiation and runout that impacted channels, woody debris management policies in small and large streams; riparian vegetation management policies; road and bridge location within valley floors; and watershed restoration structures in channels?

Methods

The channel and valley floor work utilized a hierarchical watershed approach, with basins selected to correspond with those analyzed for mass movement and road network effects in each study area, as well as additional basins outside the Blue River watershed. Eight third-, fourth- and fifth-order stream reaches were studied to evaluate the extent of flood impacts as a function of differences in lithology and the availability of sediment and wood. Measurements of flood impacted width, maximum flood water depth, location of bars, bedrock, amount of woody debris, boulders, location and species of standing and downed riparian vegetation as well as other features were made every 25 m in study reaches of 3 km or more on each stream. Stream channels above and below the entry point of debris flows were included in the study. Data were collected in a spatially-explicit manner in order to examine the contiguity of features and depositional areas.

Results

Some very dramatic examples of landscape change from the 1996 flood occurred along streams and larger rivers. In some channels, very high concentrations of bedload and accumulations of large wood accompanied the floodwaters, causing extensive erosion and incision of older deposits and surfaces, deposition of new surfaces and bars, and removal, battering or burial of riparian vegetation. Red alder (Alnus rubra) was the most prevalent riparian vegetation along the stream channels and was the species most impacted by the flood. The location of some channels shifted, as deposited wood and sediment obstructed channels and rediverted flows. Such changes affected streamside and instream structures, including roads, bridges, and stream-enhancement structures. The effects were not uniformly distributed from basin to basin, stream to stream or even from reach to reach along the same stream, however. In many cases, reaches of stream showing limited or no effects from the flood adjoined reaches showing major change.

Eight stream reaches in the McKenzie basin were inventoried, totaling over 28 km of channel. Four of the reaches had no debris flows entering directly into the study reach, while the other four had from 1 to 7 debris flows. Bankslides into the study reaches were observed in six of the streams. Two reaches did not have any debris flows or bankslides.

Understanding the geomorphic controls of spatial variation in flood response is essential to assessing the most recent flood event and to predicting channel responses to floods in the future (Montgomery and Buffington, 1993; Nakamura and Swanson, 1993; Grant and Swanson, 1995). Several bedrock study reaches received more than one debris flow per kilometer, but little evidence of debris flows remained in those channels. Constrained bedrock channels have higher shear stresses and lower resistance from channel margins than other channel types, resulting in more available energy to transport both wood and sediment downstream. In other channel types, accumulations of very large boulders were common at tributary junctions where debris flows had entered. Wood and fine sediment were transported longer distances downstream before being deposited, and in three reaches, resulted in large terminal debris jams. Smaller accumulations of wood also occurred along the high-flow stream margins. These “wood levees” then appeared to buffer the riparian areas and margins from high energy flows.

CONCLUSIONS

Multiple basin comparisons of flood response provide a very useful framework for evaluation of both intrinsic differences in flood behavior and response to differing topography, climate, landuse and geology. We are integrating our studies of hillslope and channel processes to better understand basin-level responses to floods. As part of this synthesis, we are continuing to examine results from the mass movement, road, and channel sub-components to determine how processes described in each may have contributed to disturbance cascades through flood-affected landscapes. One aspect of the interpretation will include distinguishing the effects and possible repercussions of past, present, and prospective future management practices.

ACKNOWLEDGMENTS

This research is being conducted under the Integrated Watershed Studies Component of the USFS/BLM Phase II Assessment of the flood of February, 1996 on federal lands in western Oregon and Washington. The USFS Pacific Northwest Research Station has primary responsibility for the Integrated Watershed Studies Component. The H.J. Andrews Forest Long Term Ecological Research program supported portions of the research. We thank Matt Wallenstein, Julie Donald, Ryan Ulrich, Gretchen Bolchert, and Luke Kiskaddon for assistance in the field.

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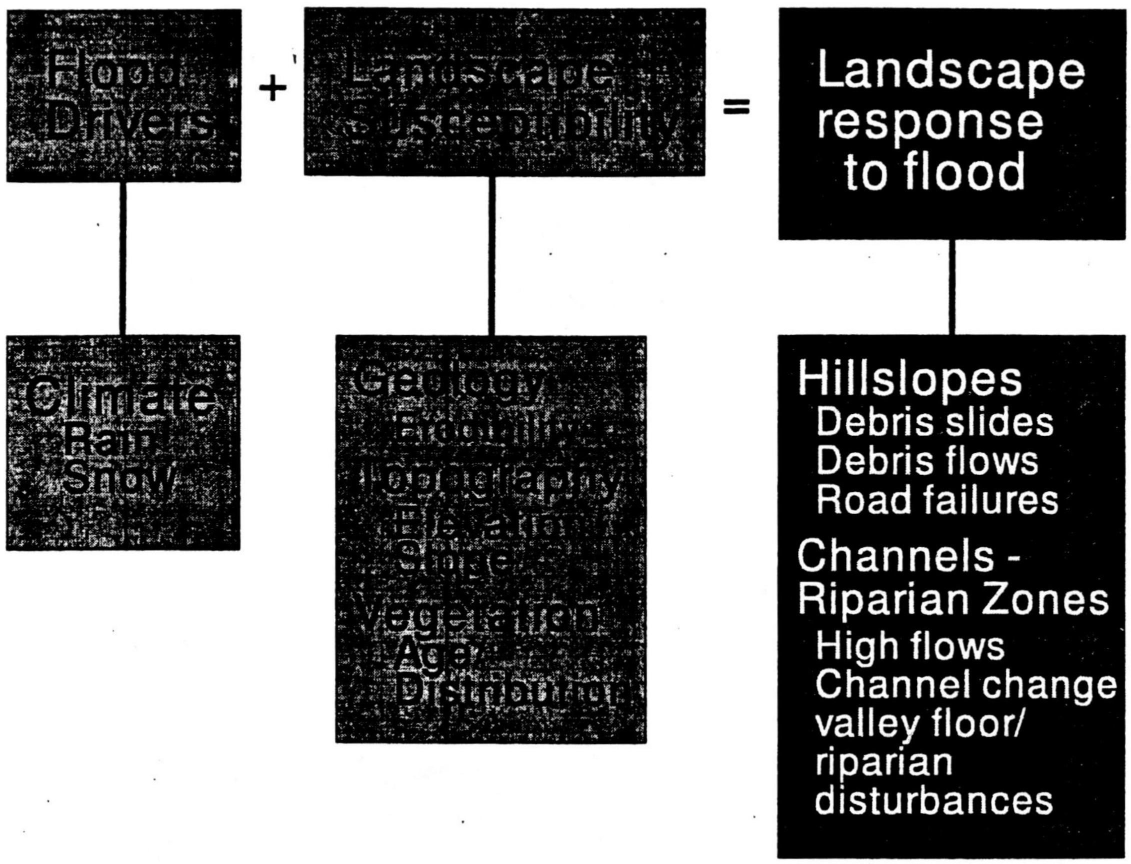

Figure 1. Interaction of climate variables with landscape conditions resulting in hillslope and channel responses. Landscape susceptibility can be viewed as a function of prior natural disturbance and landuse history in conjunction with the inherent geomorphic and vegetation conditions.

THE PACIFIC NORTHWEST FLOODS OF FEBRUARY 6-11, 1996

PROCEEDINGS OF THE PACIFIC NORTHWEST WATER ISSUES CONFERENCE

PORTLAND, OREGON, OCTOBER 7-8, 1997

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AMERICAN INSTITUTE OF HYDROLOGY

1997

Communications in regard to this publication should be sent directly to AIH, 2499 Rice St., Ste. 135, St. Paul, MN 55113-3724, Tel. (612) 484-8169, Fax (612) 484-8357, E-mail: AIHydro@aol.com.

Library of Congress Catalog Card Number is: 97-074852

Printed in the United States
10 9 8 7 6 5 4 3 2 1