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Forest engineering implication of storm-induced mass wasting in the Oregon Coast Range, USA

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Abstract

A severe winter storm, under conditions of high antecedent moisture and a substantial snow pack at higher elevations, in February of 1996 resulted in rapid flooding and a large number of precipitation-induced landslides. The number of mass wasting events greatly exceeded the expectations of many land managers, given the magnitude (50-year return interval) of the storm event. Both ground and aerial surveys were used to characterize the nature of these events and relate the occurrence of mass wasting activity to the topography, geology, and land management activities of the region. This paper is based upon an aerial videography transect of the north Oregon Coast Range and explores the potential of this technique, with special reference to storm damage assessment in commercial forestry areas. Given the efforts to enhance and protect anadromous fish-rearing habitat in the region's perennial streams, this survey explores the implications of current and past forest engineering practices, and suggests that engineering efforts to 'de-construct' the legacy of old roads and culvert systems may be appropriate in the drainage basins with the highest potential habitat values. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: landslides; videography; drainage basin; fish habitat

1. Introduction

The rugged slopes of the Oregon Coast Range rise abruptly from the Pacific Ocean, where their folded sediments and volcanic intrusives interrupt the flow of the moisture-laden subtropical jet stream, yielding orographic precipitation exceeding 2 m annually. The dense conifer forest cover and deep soils allow copious rates of infiltration and throughflow, leaving sheetwash and rainsplash as relatively ineffective sediment transport processes. The steep slopes show ample evidence of deep-seated earthflow in areas of weaker bedrock, and frequent debris avalanche activity stripping soils from the surfaces covering the more resistant volcanics. The stream channels impacted by this debris quickly winnow away the fines, leaving behind gravels and large organic debris, the materials which form the spawning beds and rearing pools for the region's anadromous fish.

Between February 6 and 8, 1996, a severe winter storm brought more than 500 mm of subtropical moisture to the northern Oregon Coast Range. Doppler radar located especially dense precipitation bands over the crest of the mountains west of Portland, OR on February 7. Given the accumulated snowpack above 900 m elevation, total runoff generated exceeded 1050 mm within 24 h along the crest of the mountains. Several local streams crested at

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levels above the previous flood of record (December 1964), and landslides blocked roads throughout the region.

The immediate impact of floods and landslide events focused the attention of both the news media and government agencies on the magnitude of the effects and their possible causes. As reports of landslides totaled in hundreds, reconnaissance surveys were hastily organized by resource management agencies (U.S. Forest Service, 1996) and environmental groups alike (Association of Forest Service Employees for Environmental Ethics, 1996). Much of the interest is prompted by concerns that the cumulative impacts of commercial forestry practices upon watersheds may seriously diminish efforts to protect and enhance the spawning habitat of anadromous salmon and steelhead runs at a time when fish counts in certain streams were at record-lows and approaching endangered status.

Initial damage reconnaissance efforts were compiled by field reports or aerial observations conducted immediately following the storm to capture the storm-induced events. These hastily implemented surveys, while responding to the immediacy of the situation, often reflect either the observational bias of the technique or the observers. Many secondary roads were blocked by slides, and field observations tended to overemphasize mass wasting activity along major highway corridors. In contrast, visual surveys by aircraft tended to concentrate on the most visible effects of the storm, mainly on managed forest lands.

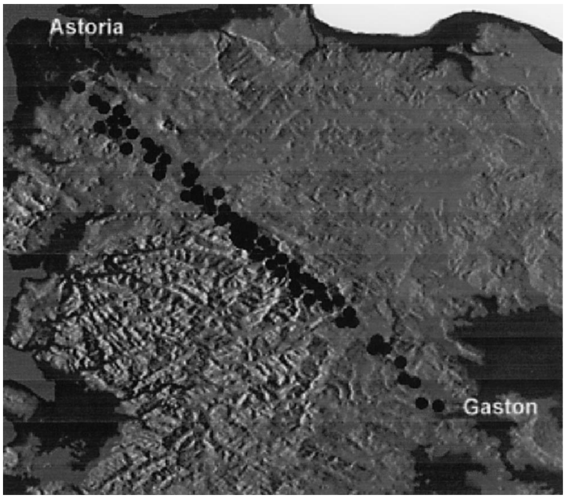

Fig. 1. Shaded relief map of the survey area, showing the location of 71 mass wasting events observed along the 109-km transect from Gaston to Astoria, OR, USA.

Fig. 2. View of a large debris torrent which scoured the channel of a perennial stream in the Upper Nehalem River watershed for a distance exceeding 3500 m.

An aerial videography mapping project was flown along the flooded banks of the Willamette and Columbia rivers on February 9 and 10, 1996 to map the extent of inundation for the Portland District, Army Corps of Engineers (Rosenfeld et al., 1996). A segment of this aerial survey flew diagonally across the northern Coast Range from Gaston to Astoria, OR as shown in Fig. 1. While this vertical imagery was not intended to sample mass wasting in this heavily impacted region, it captured a random transect which depicts 71 large-scale features related to the storm events. This imagery was interpreted and compiled to explore associations between mass wasting mechanics, morphometry, geology, and site conditions. In addition, comparisons with other contemporary surveys allow us to evaluate the potential for a more formal application of aerial videography for sampling landscape characteristics related to land management and forest engineering practices.

2. Mass wasting regimes in the coast range

Mass wasting is a dominant geomorphic process in the Oregon Coast Range, with significant mechanisms ranging from soil creep due to frost heave (pipkrake) to deep-seated rotational slides. Activity is concentrated in the winter months (December through March) and is usually associated with significant precipitation or snow-melt events. The micromorphology of most slopes in the coast range is a complex of overlapping landslide hollows of varying age, interspersed by debris fans and hummocky toe slopes.

Shively (1989) carefully examined such a hillslope complex and determined the magnitude and frequency of mass wasting events over the past 250 years using dendrochronology. By delineating 25 of the dated mass wasting features and applying the morphometric indices of Crozier (1973) , the 'classification index' (D/L) used by Skempton (1953) was clearly proven to be a reliable indicator of mass wasting type. Additionally, clustered dates indicate a 'peak periodicity' of 20–30 years in mass wasting frequency. Dietrich et al. (1982) recognize mass wasting as a primary component of sediment budgets in northwest watersheds, and illustrate that progressively older landslide scars fill with increasingly finer materials. They also point out that debris flow materials are frequently deposited in active channels where fines are removed by channel flows, leaving behind cobbles and gravel in the channel bed.

Wong (1991) monitored the movement characteristics of landslides in the coast range over a 10-year period. In his observations, all the landslides exhibited brief movement in response to significant precipitation ($>$ 160 mm threshold) events, with a lag time of less than 3 days. All major movements ($>$ 10 mm in 4–10 days) were precipitation-induced.

Fig. 3. Multiple shallow slides and debris torrents are seen here in a photo over the sedimentary terrain near the middle of the survey transect.

Three large-scale mass wasting regimes in the coast range landscape were observed in our study: (1) shallow debris slides/torrents; (2) deep-seated slump/earthflow; and (3) saturated streambank failures. Each of these regimes occurs in a variety of settings and often involves a variety of processes and potential influencing factors.

Over half of the events observed were shallow debris slides or torrents. Typically, these events occurred on steep slopes ($> 30°$) and were predominantly associated with sedimentary bedrock. Depth estimates range from 2 to 5 m, with maximum length exceeding 3000 m (Fig. 2). Topographically, 71% of the debris slides originated in swales along steep slopes, with 32% of the events delivering sediment to ephemeral channels with over 50% directly impacting perennial channels. These impacts include both channel scour (sometimes exposing bedrock) and deposition of landslide and large organic debris. Since these events were precipitation-induced, the flow in the channels was sufficient to 'wash' the landslide debris, and no channel impoundments were observed. Although these events resulted in significant turbidity along the affected streams, most perennial channels quickly developed gravel bars and pools along their affected reaches (Fig. 2). In some cases, however, ephemeral channels along slopes were scoured into bedrock sluices (Fig. 3).

A combination of high water and significant throughflow from the valley walls created favorable conditions for saturated earthflow along the banks of perennial streams. These situations were characterized by multiple 'retrograde' tension cracks parallel to the stream bank, toppling trees in the riparian zone and resulting in bank-attached bar development immediately downstream (Fig. 4). These 'saturation failures' along the banks were frequently obscured from direct observation in the video imagery by riparian tree canopy, and their presence was signaled by multiple downed trees and fresh debris in the

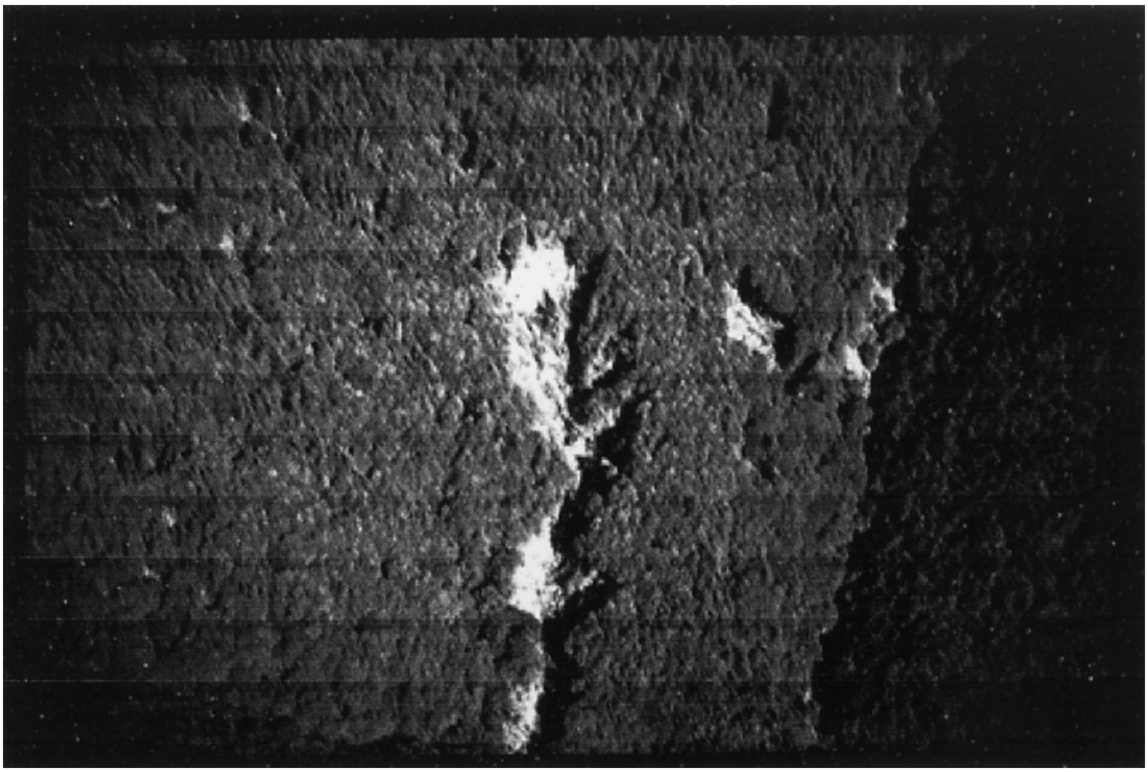

Fig. 4. Shallow slides dominate the slope in the center of this image, while toppled trees give evidence of saturated bank failure along the channel at the right.

Fig. 5. An earlier slump-earthflow with evidence of subsequent motion is typical of deep-seated failures whose response to precipitation events is difficult to document.

channels. While this mass wasting type comprised 38% of the events, it was difficult to estimate the volume or measure the morphometric indices for individual events. Seven of these 25 events occurred in colluvium from sedimentary slopes, and 18 occurred in alluvium.

Deep-seated slump/earthflow failures occurred in only 9% of the observed events, and all, but one, were along a slope underlain by soft sedimentary rocks. Whether these were new failures or re-activations of earlier events is unclear (Fig. 5), although each exhibited signs of recent deformation and sediment contribution along its flanks. Undoubtedly, movements along many such previous failures probably went 'undetected' in our survey.

3. Storm-induced mass wasting implications

Intensive commercial forestry in the coast range has altered the natural geomorphic system. Access roads which traverse the steep slopes often interrupt the throughflow, concentrating water as runoff in the ditches and culverts. Unless drainage is carefully controlled, saturated roadbeds and culvert outlets often become source areas for debris avalanches. Clearcuts and thinned forest canopy expose remaining trees to wind stress, increasing the potential of blow-down, which in turn exposes bare soil and encourages saturation failures. The frequency of storm-induced events resulting from the February 1996 storm quickly became an issue of public concern which challenged the concept of 'acceptable forestry practices' with respect to public safety and environmental values (Rozek, 1997).

Research linking fish population dynamics to land management activities has evoked changes in management practices on both public and private lands, designed to protect watershed values and remediate declining channel and riparian habitat conditions. While modern forest management practices increase the frequency and size of road culverts and promote tree harvest using cable suspension systems to reduce the effects of soil compaction, these 'best management practices' are relatively recent developments.

Large-magnitude storms often trigger geomorphic responses from older management practices, known as 'legacy features', especially when the magnitude of the event exceeds the 50-year return interval. Failures are often associated with clogged or collapsed culverts on abandoned forest roads. An effective technique is the removal of old culverts on unused roads, leaving open trenches across the former road prism, or the construction of 'water bars' to deflect surface runoff from forest roads downslope at frequent intervals. The costs associated with de-engineering unused roads are generally considered excessive by the forest industry, and management requirements for access during 'pre-commercial thinning' and later 'commercial thinning' at roughly 15-year intervals are cited as justifications for not eliminating unused roads. As a result, the anticipated benefits of modern forest practices are sometimes obscured by disturbances related to older management techniques or to the lack of maintenance on remaining 'legacy' road or culvert systems.

In an effort to evaluate the effects of the February 1996 storm event on the present characteristics of the Oregon Coast Range, the individual landslide events observed on our videography transect were interpreted to determine several relevant landscape asso-

Geology:	Volcanic	Sedimentary	Alluvium
Deep Seated	1	5	
Debris Avalanche	9	23	3
Saturated Earthflow		7	18

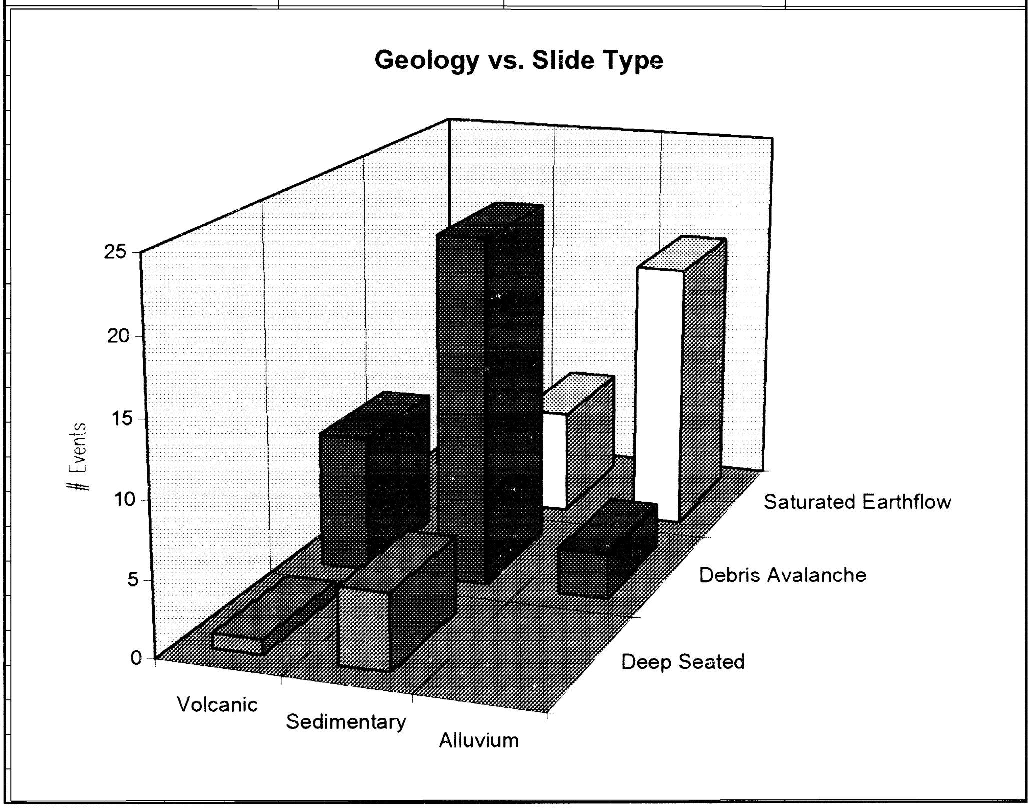

Fig. 6. The relationship of bedrock type to failure mechanisms in the events observed in this survey.

ciations. The mass wasting mechanics factors included a subjective classification of the character of the event and its rate of material displacement. When possible, the event was associated with the mapped bedrock type, grouped into three classes: sedimentary rock (principally sandstone and mudstone), volcanic rock (basalt and breccia), and alluvium (valley fill and channel bank deposits).

Some very clear relationships related to the mechanics of the individual events are seen in Fig. 6. Almost all occurrences of alluvial material failures were classed as saturated earthflow and bank failures of slow to moderate motion rates. Although most rapid debris slides/avalanches occurred in sedimentary bedrock areas, these failures evenly reflect the distribution of volcanic and sedimentary bedrock types along our transect.

These data also demonstrate the significance of topographic position and landform slope as controlling factors in the type and rate of mass wasting events (Fig. 7). The classification (D/L ratio) index of Crozier (1973) was used to further explore the relationship between the morphometry of the landslide events and the topographic position and forest cover type of the initial failure (Fig. 8). The classification index is based on length measurements and depth of failure estimates. Although the videography may be viewed in 'stereo', the depth estimates are rough at best. We estimated shallow failures at < 2 m, intermediate depths at 5 m, and deep-seated failures at > 10 m. This divides topographic position into six classes: roads and timber harvest landing areas; significant breaks in slope of greater than 15°; swales along valley-side slopes; footslope areas with colluvial transitions to valley bottoms; lower banks adjacent to stream channels; and other locations such as divides or debris fans. Drainage swales and bedrock-controlled 'slope breaks' dominated the failure areas on 'natural' slopes, with man-made sites (mainly roads) contributing 42% of the total slope

D/L Ratio	1-5	<10	<15	<20
Other	1			
Footslope	1	3	1	
Road/Culvert	6	5	1	1
Swale	6	7	7	
Slopebreak	6	3	2	4
Streambank	6	10		

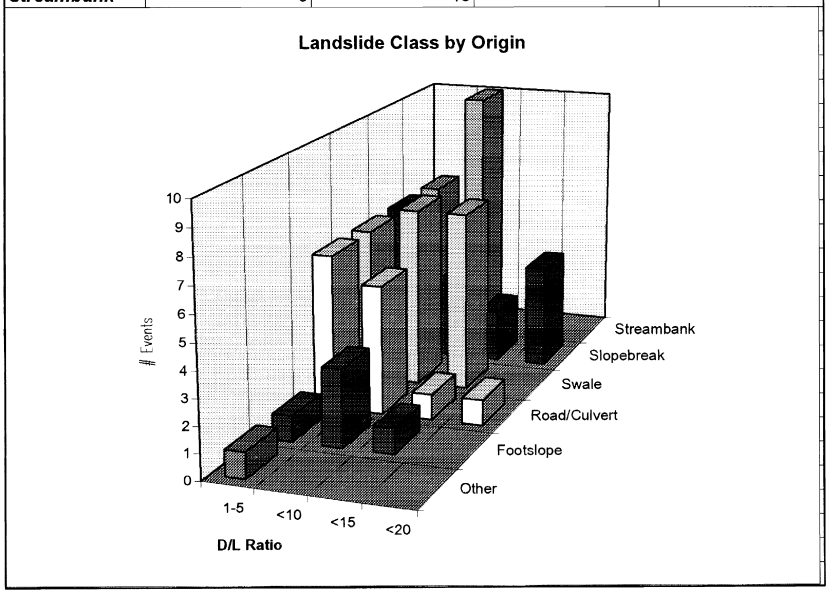

Fig. 7. The relationship of topographic position and roads to the depth/length (D/L) ratio.

D/L Classification Ratio	1-5	<10	<15	<20
Other	1	1	1	1
Mature Forest	2		1	1
Thinned Forest	5	9	4	2
Clearcut/Restock	18	18	5	3

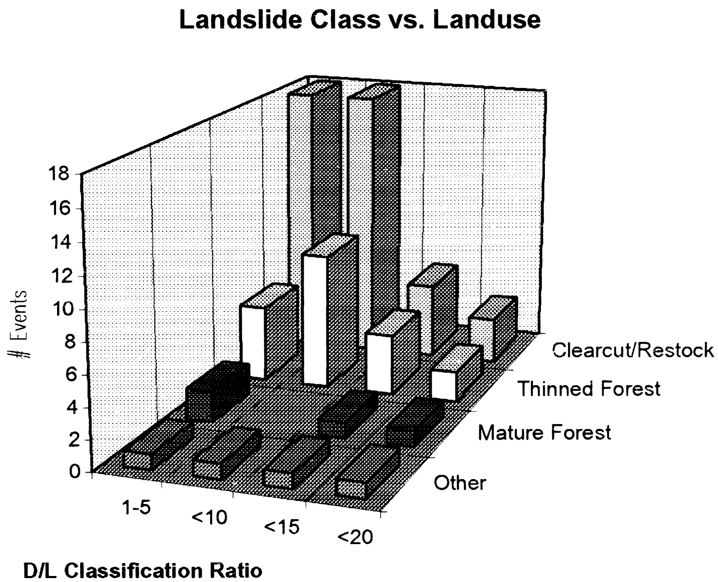

Fig. 8. The number of events in each landslide class by land cover characteristics.

failures. The debris avalanches and torrents were the most obvious events seen in our aerial survey and were the events which visually attracted our attention during our flight. These events dominated the valley-side slopes of the mountains and were most apparent when they originated in replanted managed forest areas.

Alluvial materials, confined to generally low-gradient valley bottom areas, dominated the moderate rate events. The actual number of such events observed in our aerial survey probably underestimates the actual number of such events significantly, as our observations were limited to areas where obvious disturbance of trees in the riparian corridor and in-stream deposition were seen in the imagery. Wooded riparian 'buffer strips' are zones of intensive vegetation adjacent to stream channels designed to capture return flow and provide shade to reduce stream temperatures in forest harvest areas. Many other small alluvial bank failures, without major vegetation disturbances, were hidden under the canopy of riparian trees and were not included in our tallies.

Topographically, the sedimentary bedrock typically underlies moderate to steep (15°–60°) slopes, with volcanic intrusives boldly forming ridges and peaks at very steep (50°–80°) angles. As a result, most debris torrents occurred in sedimentary terrains, with rockfall and debris avalanches on very steep slopes in mainly volcanic areas (Fig. 9). Deep-seated slump and earthflow events were observed in sedimentary areas; however, the number of events was

Fig. 9. A rockfall-debris avalanche in steep volcanic terrane.

not significant. Additionally, it was almost impossible to determine if these events were initiated by the storm event in question, or if a re-activation of a pre-existing failure had occurred.

When we examine the forested sites classified as mature (multi-canopy) forest, thinned (even canopy) forest, or clearcut and unthinned plantations, the relationships become even more interesting. Road and landing-associated failure sites all occurred in managed forest areas, with the larger debris torrents mainly starting in thinned forest stands. It is unclear from our study whether these observations result from smaller failures being 'hidden' by taller forest canopy, or perhaps that harvest activity in thinned stands occurred 25–40 years ago under less demanding forest management practices which have yielded more frequent failures. Another curious association was that although mature multi-canopy forest occupied only about 2% of the area covered by our aerial imagery, this class of land cover yielded 9% of the failures. It is proposed by this observer that what remains of old growth forest cover is frequently found in very steep or unstable areas, where the economics of forest is impractical, but where the conditions for mass wasting may be more pronounced.

Failures along drainage swales tended to occur along the upper slope, just below Horton's zone of 'no erosion' (Fig. 10). All of these occurrences were observed in areas of managed forest, with the larger volume slides associated mainly with thinned middle-aged stands. It is unlikely that observational error would account for this relationship, and the author suggests that wind-toppled trees exposed deeper 'root throw' on the older stands, resulting in larger volume debris torrents and avalanches. Elevation and aspect played an apparently significant role in shallow debris slides, with north-facing slopes accounting for nearly 80% of the slides above 800 m. This is attributed to frost heave which effectively decoupled surface soils when the warm rains saturated the ice-needle-inflated surfaces.

To understand the implications of these storm-induced failures upon watershed values, the contribution of debris directly to ephemeral and perennial channels was recorded (Fig. 11). Direct sediment contribution to channels occurred in 83% of the total number of events in our survey. Given the precipitation intensity at the time of the storm, it may be assumed that active flow was occurring in all of the channels surveyed. However, channel flow normally does not occur in the small first- and second-order channels during the drier summer months, and such channels were noted in our observations. Neither size of the event, nor the velocity (which would extend its effects along a channel) had any apparent relationship with the types of channels affected. In other words, channels of all orders were apparently directly affected by mass wasting in equal proportion. Mass wasting debris deposited by a storm in February will be washed by higher winter flow discharges which wash away fine sediment, leaving the gravel and cobble fraction as bars and riffles (Fig. 12). Although the short-term turbidity resulting from this sorting process may inhibit anadromous fish migration up the streams, the resulting gravel beds and

Fig. 10. Multiple debris avalanches occurring in adjacent swales along a sandstone ridge.

riffle/pool sequences will provide future spawning reaches.

4. Conclusions

The data derived from our survey are not claimed to be representative of the mass wasting character of the entire Oregon Coast Range, neither is it a random sample in any statistically defined sense. This survey resulted from an opportunity which happened to coincide in time and space with a significant geomorphic 'threshold' event that triggered numerous discrete mass wasting occurrences. Our survey is simply an opportunity to examine the future use of aerial video imagery to collect data about mass wasting features, hopefully according to a planned sampling design. The types and accuracy of the data obtained in this survey are very promising, especially since the aerial acquisition technique is both low-cost and near real-time. Future research should focus on ground verification of imagery interpretation, accuracy of size and class estimates, and the frequency of detection of these features. Nonetheless, this survey has revealed some interesting process, landform, and management associations pertaining to storm-induced mass wasting events which merit further discussion.

Our overall survey observations would tend to confirm the significance of storm-induced mass wasting triggers as a pervasive geomorphic process in the Oregon Coast Range. However, the association between mass wasting events and forest management activities provides some challenges to our current concepts of watershed management. It is clear that large storms actually initiate failures resulting from 'legacy' features, producing impacts that reflect past management activities. While it is encouraging that newer road and culvert installations were related to fewer mass wasting events, the north coast range watersheds are more likely to be dominated by events related to older-style management

Sediment Delivery	Indirect	Ephemeral Channel	Perennial Channel
Rapid	2	8	12
Fast	5	5	10
Moderate	2	2	7
Slow	3	3	7

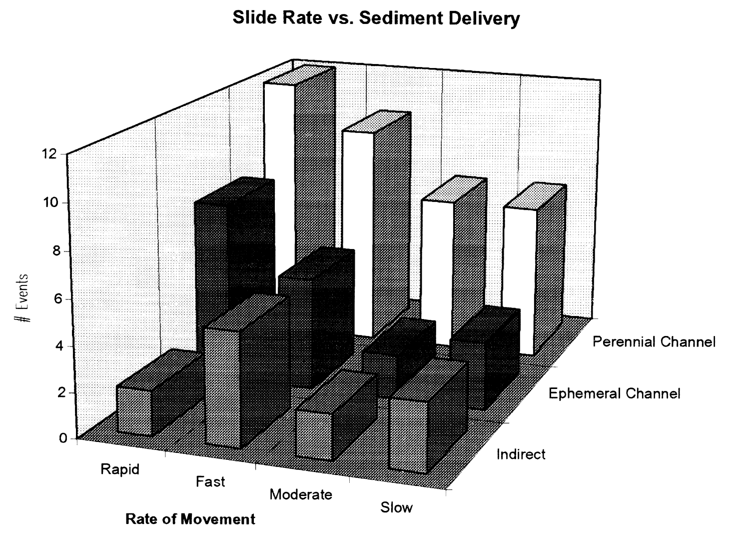

Fig. 11. The effects on sediment delivery by estimated velocity of the event.

activities for years to come. The argument against deconstructing unused forest roads on the basis of reuse for thinning operations or fire management must be reconsidered. The economics of forest harvest and fire suppression must be balanced against the potential for mass wasting impacts upon channel configuration and riparian habitat values.

Watershed managers and forest engineers can gain some insight from these initial findings while continuing to make progress in how forest management is conducted. We must, however, recognize that aquatic habitat recovery may really require us to engineer the removal of older roads and improve upon slope drainage in key spawning watersheds. Otherwise, the benefits of improved engineering practice may be masked by low-frequency/high-magnitude events that could reverse the progress anticipated on watersheds requiring immediate protection and restoration. Current restoration policies spread management funds across a wide spectrum of managed forests to optimize the areal extent of habitat improvement. It is apparent from our findings that engineering solutions to preclude major storm effects must go far beyond enlarged culvert diameters and 'clog-proof' interceptor designs. Engineers must adopt a minimum impact strategy for initial road design, perhaps including temporary devices such as military-style vehicle-emplaced bridging, which would be removed immediately after each management activity. Forest managers must accept that the costs of these engineered activities will increase management costs, but will reduce restoration costs over time.

It appears from our observations that larger trees (i.e., deeper roots) may be associated with deeper and larger debris torrents and avalanches. The higher-than-expected frequency of failures originating in mature forest stands may be an indication of the geomorphic character of the remaining 'old growth' forest stands in the coast range. Mature forest stand locations are remnants of ancient forests left unharvested by difficulty of access, poor condition, or occupation by an identified threatened species. Analysis of wind exposure, soil sensitivity, and slope stability should be used to provide 'edge

Fig. 12. A debris avalanche ‘track’ carried a large volume of material across the floodplain, and formed new bars downstream in the perennial channel.

buffers’ around sensitive stands. In such extreme geomorphic settings, almost any management activity would likely result in potentially severe mass wasting impacts to the watersheds over time.

As channel deposition of mass wasting debris occurred from most events observed, regardless of the origin or mechanics of the slide, the impacts on the aquatic ecosystem merit further research. Equally important was the fact that all classes of channels were involved. This implies that efforts to enhance anadromous fish habitat should take into consideration the magnitude and frequency of debris contributions, the positive aspects of mass wasting as a source of spawning gravel and large woody debris, as well as the negative effects.

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