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Effects of Earthflows on Stream Channel and Valley Floor Morphology Western Cascade Range, Oregon

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Title: Effects of Earthflows on Stream Channel and Valley Floor Morphology, Western Cascade Range, Oregon

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Slow moving earthflows (0.1 - 15 m/yr.) may constrict valley floors and directly impinge on stream channels. Earthflows that move laterally into channels deliver organic and inorganic material to the stream from the earthflow toe. If the amount and particle size of this material is too large to be removed by streamflow, aggradation and subsequent steepening of the channel gradient occur. However, if the rate of material input is too slow or the size of material is too small, the material can be removed as bedload or suspended sediment load and there will be no change in gradient. Where earthflow encroachment causes channel aggradation, the valley floor and channel upstream of the zone of direct earthflow constriction experiences widening and decrease in the gradient of the valley floor and channel. This increase in width of the channel is due to the gradient change in the earthflow-constricted zone and to hydraulic backwater effects at stream flows which carry bedload.

Effects of the earthflow constriction at five sites in the western Cascade Range of Oregon are examined at two scales 1) that of stream reaches (10^2 to 10^3 meters of channel length in areas having similiar valley floor characteristics) and 2) that of channel units (features which are 1 to 10 channel widths in length, e.g. pools, riffles and cascades). In earthflow-constricted reaches (defined by length of the earthflow toe entering the channel) where channel gradient is steepest, there is a greater percentage of cascades per unit of reach length. The reach upstream of these constrictions contain the lowest percentage of cascades per unit of reach length, but the highest percentage of riffles.

Three of the five earthflows studied followed the patttern of steeper gradients in the earthflow-constricted reaches. This pattern was not evident in the other two sites, apparently because of the size and rate of the material entering the channel from the earthflow, as well as the over all gradient of the channel which may limit other changes in gradient.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Effects of Earthflows on Stream channel and Valley Floor Morphology, Western Cascade Range, Oregon

INTRODUCTION

The steep hillslopes of the western Cascade Ranges are prone to different forms of mass movements including debris flows, shallow landslides, and deep seated earthflows. Each movement type locally affects hillslope characteristics, and may affect stream channel and valley floor morphology. Rapid mass movements, such as landslides and debris flows, affect the channel and valley floor by adding sediment rapidly to the features, changing the valley-floor morphology at least over the short term.

Slow moving earthflows may constrict the channel and the valley floor. Since earthflow movement is chronic, constriction is persistent, and recovery is a long term process. Earthflow movement rates may vary from year to year, however earthflow activity may occur over 100's to 1000's of years. Persistant earthflow movement not only constricts the channel, it also disrupts the earthflow surface and the vegetation growing on it.

There has been little study of the effects of earthflow constriction on channel and valley floor morphology. The purpose of this paper is to decribe the changes earthflows have wrought on the channels and valley floors in the western Cascades of Oregon. Five earthflows within the Willamette River Basin are used as examples.

CHAPTER 1

OVERVIEW OF EARTHFLOW - STREAM CHANNEL INTERACTIONS

Earthflow characteristics

Earthflow movement is characterized by deep seated translational sliding and rotational slumping along a complex concave glide plane (Swanson and Swanston, 1977; Varnes, 1978; Bovis, 1985). The movement occurs in a pluglike fashion with primary movement occurring in a thin basal slip (Bovis, 1985). The surface topography is usually hummocky with scarps and benches, and is broken by shear zones and tension cracks.

Earthflows vary in size. Swanson and Swanston (1977) describe earthflows in the Pacific Northwest that range in size from one hectare to several square kilometers. The larger earthflows may be complexes with some, none, or all of the complex moving at a given time. Bovis (1985) noted that many of the earthflows examined in the interior plateau of southwest British Columbia have large dormant areas bordering the presently active zones, suggesting that in the recent past there was more vigorous earthflow activity.

Earthflow movement is variable spatially and temporally (Swanson and Swanston, 1977; Iverson, 1986). Portions of one feature may be moving at different rates. Bovis (1986) attributes the longitudinal variability of movement rates to extensional and compressional soil flow zones. Earthflow velocities in the western Cascades range from 0.01 to 15 m./yr (Swanson _et_. _al_., 1985). Earthflow activity may vary in response to large scale climatic changes or due to smaller scale, seasonal fluctuations which are responsible for changes in piezometric head (Swanson and Swanston,1977; Bovis, 1986). Iverson and Major (1987) stated that local groundwater circulation and perturbations when the earthflow is saturated cause local areas of instability and movement. The western Cascade earthflows examined in this study exhibit seasonal patterns of movement (Swanson and Swanston, 1977; Hicks, 1982). Monitoring of three earthflows in the western Cascades by the PNW Research Laboratory project 4302 indicates that the Jude Creek (Hicks, 1982) and Lookout Creek earthflows (Swanson and James, 1975; Swanson and Swanston, 1977; and others) undergo summer dormant periods as piezometric head drops, but begin to move again during the wet winter months. The Middle Santiam slide (Hicks, 1982) moves all year round (G. Lienkaemper pers. comm.) but during the summer months moves at reduced rates.

Channel characteristics

Third- to fifth-order stream channels in the western Cascade Range are primarily straight and high gradient; average channel gradients range from 0.02 to 0.10. Mean unvegetated channel width, referred to as the active channel width, range from 8 to 20 meters. Mean valley floor widths generally range from 1 to 5 active channel widths; however, they can be wider.

A hierarchical approach to valley floor and channel classification divides valley floors into reaches based on morphology, and the channel within the reaches into channel units (Fig. 1), providing a useful framework for evaluating effects of

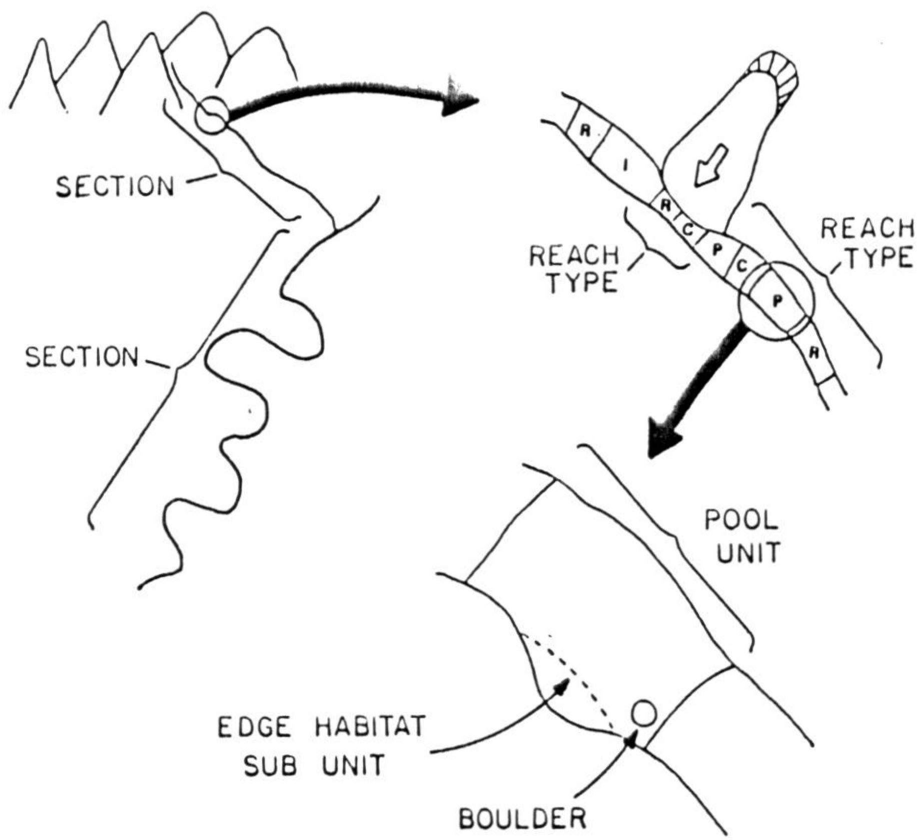

Figure 1 - Hierarchical approach to valley floor and channel classification. (After Swanson et. al., in press).

earthflows on valley floor and channel morphology (Swanson et. al, in press). Reaches are distinguished by the overall valley floor width extending over 100's to 1000's of meters of stream length and the interactions of the hillslopes with the valley floor and channel. The two main reach types are constrained and unconstrained. Constrained reaches have narrow valley floors (active valley floor width less than 2 active channel widths) resulting from constraints such as bedrock, and constricting agents such as alluvial fans, and earthflows. Active valley floor is defined as the collective width of the channel, floodplain and low terraces less than 3 meters above low flow water level. Relatively unconstrained reach have wider active valley floors. This study examines earthflow-constricted reaches and the adjacent upstream and downstream reaches.

Channel units and their distribution can be used to define the morphology of the channel within reaches. Four principal channel units are used in this study: pools, riffles, rapids, and cascades. These units are defined during low flow by their gradient and a visual estimate of the area in supercritical flow (Grant, 1986). Units are usually at least one channel width in length; the exception is in cascades, which include the units termed bedrock steps, bedrock falls, and log falls by Grant (1986). Pools are the lowest gradient unit (less than 0.01), and have little or no supercritical flow. Riffles have slightly steeper gradients (0.01-0.025), are shallow, and have up to 30 % of the water surface broken by supercritical flow. Rapids are transitional units between riffle and cascades, having slopes between 0.02 and 0.05, with high amounts of supercritical flow up to 55%. Rapids contain many large roughness objects, but steps, if at all evident, are not pronounced and do not fully cross the channel width. Cascades are the steepest units and contain ribs and falls. Cascade gradients can range from 0.04 to 0.30. Cascades are dominated by large boulders and cobbles, which can be grouped into steps that completely cross the channel (Grant, 1986).

Channel units and channel geometry are directly influenced by exogenous materials such as large woody debris, bedrock, and large boulders (Grant, 1986; Lisle, 1987). Exogenous material changes the flow patterns, and may also be the cause of channel unit position within a reach.

Interactions between earthflows, channels, and valley floors

The relation between direction of earthflow movement and stream channels varies widely within a basin, but falls into three categories (Fig. 2). Small earthflows may move onto surfaces such as terraces, and not impinge on the streams (Fig. 2a). Direction of earthflow movement may be downvalley, parallel to the main stream draining from the earthflow toe (Fig. 2b). Earthflows may also move laterally into a stream channel (Fig. 2c). This study examines the effects of lateral earthflow encroachment on channels.

Channel and valley-floor constriction are probable results of earthflow encroachment. Another, possible result is an increase in channel bed elevation, and therefore an increase in local channel slope, due to the input of coarse material from the earthflow toe

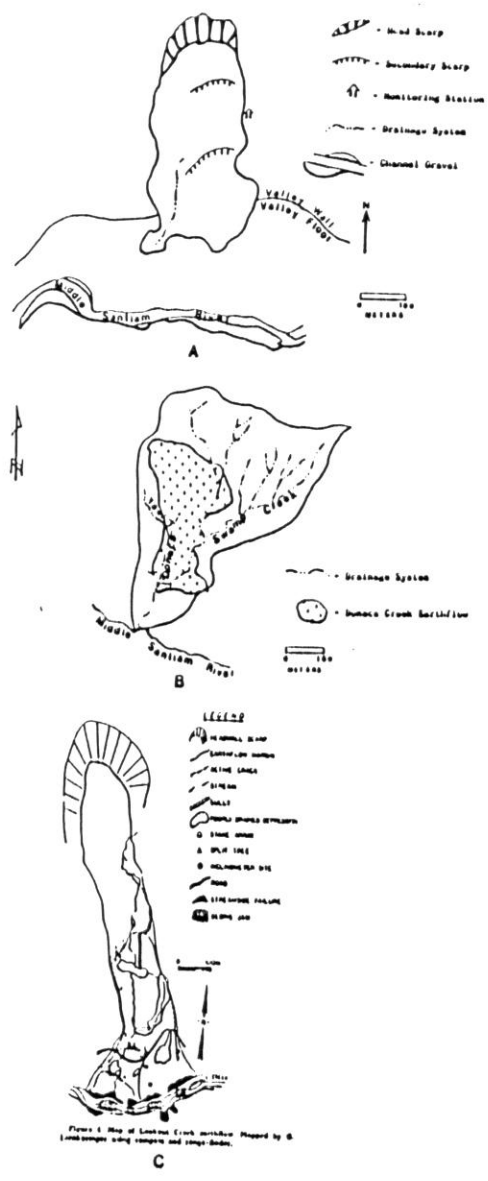

Figure 2 - Earthflow movement in relation to drainage patterns. A) The Middle Santiam Slide moves downslope but does not impinge on a creek. B) The Donaca Creek Earthflow moves parallel to the Swamp Creek drainage, a tributary of the Middle Santiam River (from Hicks, 1982). C) The Lookout Creek Earthflow moves laterally into Lookout Creek (from Swanson and Swanston, 1977).

and from the opposite valley wall (Kelsey, 1977; Swanson et. al., 1985). Increase in bed elevation is dependent on the size of the channel that the earthflow is impinging on, the size of the earthflow, earthflow velocity, and particularly the size of material being delivered by the earthflow to the stream (Swanson et. al., 1985). If the drainage area is large, thereby having high stream power, the stream is more capable to move particles that enter from the earthflow. Large channels may be capable of moving all sediment supplied from the earthflow toe, thereby preventing channel aggradation. Lower-order channels having lower stream powers are likely to be more affècted by earthflow sedimentation.

Size distribution of material entering a channel from an earthflow toe is highly variable, ranging from clay and sand to large cobbles and boulders. The size distribution is determined by the rock type and by the degree of weathering. Organic material is also emplaced in the channel from the earthflow. Material from the bank opposite the earthflow toe is another source of organic and inorganic material.

Channel size and rate of material delivery from the earthflow toe are important factors in determining the magnitude of earthflow impact on channel morphology. Rate of material delivery is directly related to earthflow velocity (Swanson et. al, 1985). The channel constriction ratio (C.R.) relates earthflow velocity to channel width in the area of impingement:

$$C.R.=(\text{earthflow velocity}/\text{channel width})\times 100.$$

As earthflow velocity increases, the channel constriction ratio increases (Fig. 3). Studies by Swanson et. al. (1985) on the Lookout Creek and the Jude Creek earthflows indicates that sediment delivery by the earthflow to the channel at sites with low constriction ratios (Lookout Creek; C.R.=1.1) is episodic, while sites with extremely high constriction ratios (Jude Creek; C.R.=200) have persistently high sediment delivery rates with slumps and small landslides off the earthflow toe delivering material every winter.

The size and geometry of earthflows and valley floors control the type and magnitude of geomorphic change an earthflow imposes on channel and valley floor morphologies. The length of the earthflow toe that impinges on a channel determines the length of channel over which the channel slope can be increased. Stream discharge determines the size and amount of material that can removed from the toe area, thereby regulating the amount of gradient change caused by channel aggradation. Aggradation in the constricted reach of fourth- to fifth-order channels may cause an increase in channel slope in the constricted area (Kelsey, 1977; Swanson and Swanston, 1977). It may also cause development of lower stream gradients and wider valley floors in the reach directly above the constriction (Swanson et. al, 1985). The effect of similar amounts of channel aggradation in lower order channels may be less pronounced, however, due to the high channel gradients and confinement of valley floors by bedrock in small steep streams (Swanson et. al., 1985).

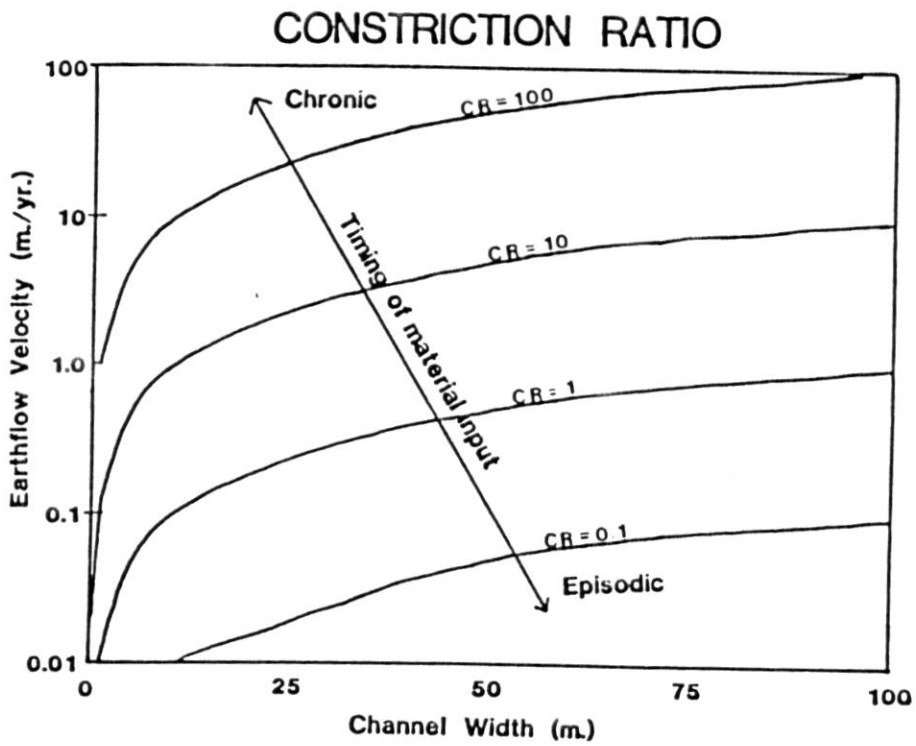

Figure 3 - Semi-logarithmic plot of earthflow velocity, channel width, and earthflow constriction ratio (C.R.) in relation to frequency of sediment delivery. C.R. = earthflow velocity/channel width x 100.

Hypotheses

Each study site is composed of the three reaches. In some cases the reach downstream from the constriction is similar in channel and valley-floor geometry to its area prior to earthflow encroachment. However, this is not a valid assumption where there are strong contrasts in geotechnical properties of bedrock and surficial deposits among the three reaches. The earthflow-constricted reach is directly affected by the earthflow constriction of the valley floor and channel. The upstream reach is indirectly affected by the changes in the earthflow-constricted reach (Figs. 4 and 5; Table 1).

Coarse material placed in the channel from the earthflow toe and the valley-wall opposite the earthflow, will cause aggradation and, greater numbers and/or greater extent of cascade units; therefore, a greater channel gradient through the reach (Fig. 5). The constriction of the valley floor by the earthflow may decrease the width of the active channel.

The steep slope in the earthflow-constricted reach and the channel constriction cause the formation of a hydraulic backwater upstream of the constriction. Increased sediment deposition can cause channel avulsions, and formation of braid bars or point bars. These low bars increase active channel width in the upper reach. The increased channel width will, in turn, decrease flow depth and velocities, thereby reducing the sediment transport capability of the channel, and causing further deposition. This may lead to deposition in the upper reach and a decrease in the upper reach slope.

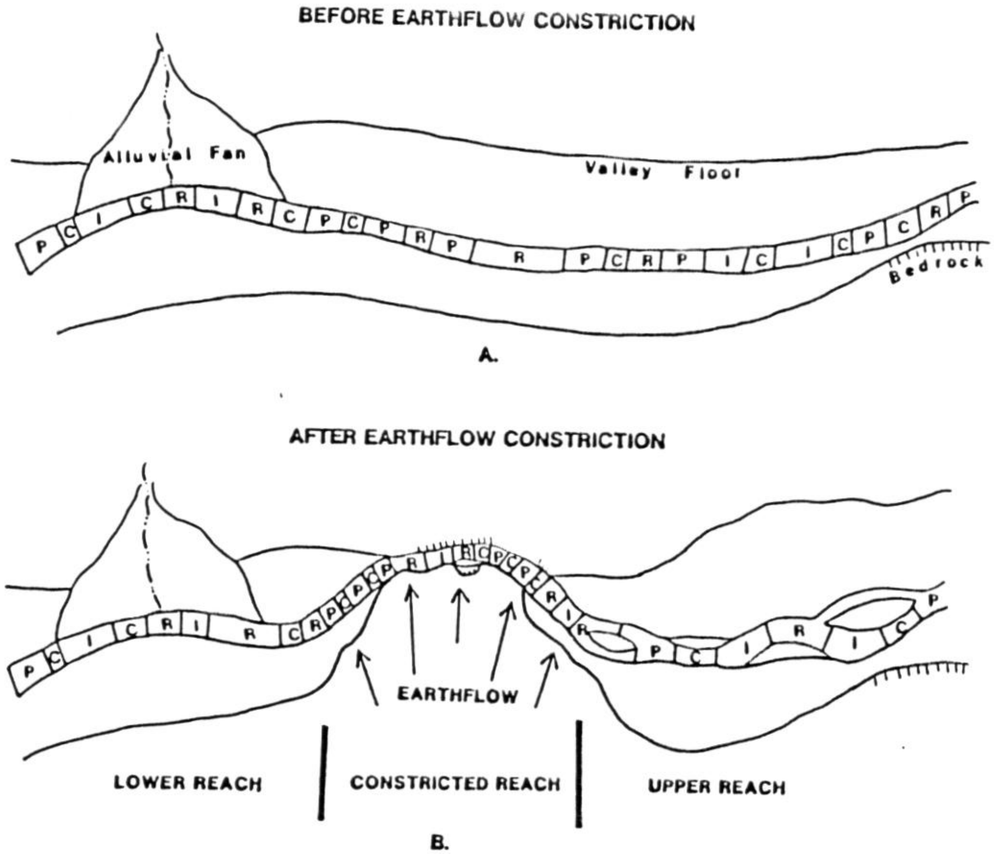

Figure 4 - Schematic representation of hypothesized changes in channel unit configuration and total valley floor width that occur because of earthflow constriction. A) Channel system before earthflow constriction, showing alluvial fan and bedrock as valley floor constrictions. B) Channel system after earthflow constriction, note change in channel unit types in the upper and constrained reaches, as well as the increase in valley floor width upstream of the constriction. P = pools, I = riffles, R = rapids, and C = cascades.

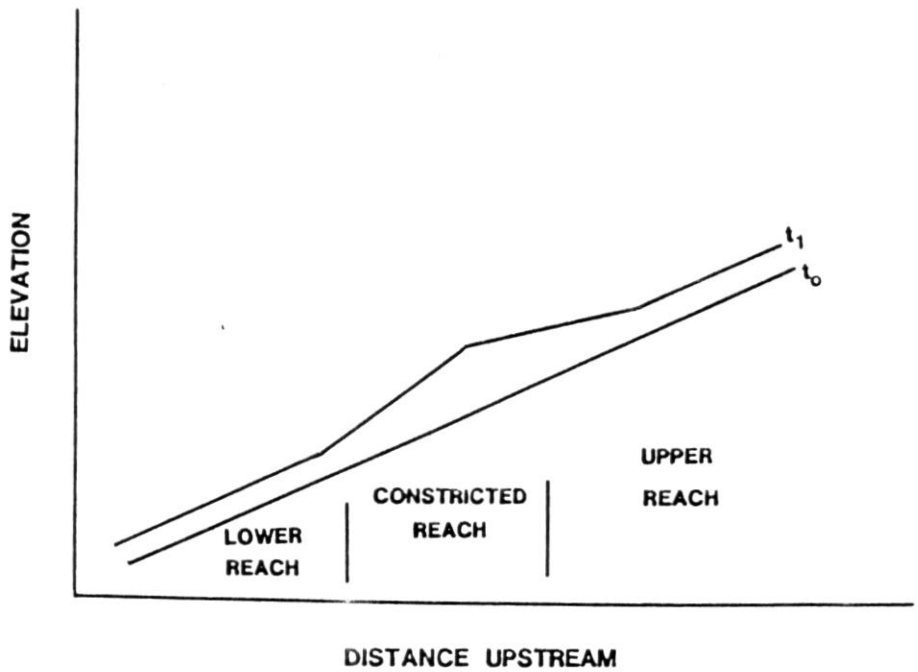

Figure 5 - Schematic representation of the hypothesized changes that occur to the longitudinal profiles. t_o is pre-earthflow, t_1 is after earthflow constriction. The elevation of the lower reach in t_1 is equal to that at t_o.

	REACH		
	LOWER	CONSTRAINED	UPPER
RELATIVE REACH GRADIENT	LOWEST TO INTERMEDIATE	HIGHEST	LOWEST
PARTICLE SIZE	FINE TO COARSE	VERY COARSE	FINE
RELATIVE ACTIVE CHANNEL WIDTH	INTERMEDIATE	NARROWEST	WIDEST
RELATIVE VALLEY FLOOR WIDTH	INTERMEDIATE	NARROWEST	WIDEST
VALLEY FLOOR SURFACE TYPES	LOW TO HIGH TERRACES FLUVIAL AND GLACIAL ORIGIN	VERY FEW VALLEY FLOOR SURFACES	LOW TERRACES SECONDARY CHANNELS

Table 1 - Hypothesized relative differences in channel characteristics between reaches due to earthflow constriction.

Very few changes are hypothesized to occur in the reach downstream from the earthflow. There may be increased deposition, as material moves through the steep constricted reach and then encounters a break in slope between the earthflow reach and the less-steep lower reach. There may be more large boulders in the lower reach, since boulders may move downstream from the earthflow reach.

Channel units in the constricted reach are expected to be shorter and narrower than those in the other reaches. Channel units of the upper reach may be wider, and possibly longer, than the channel units in the lower reach.

STUDY SITES

Five sites were chosen for study (Table 2, Fig. 6). A sixth site, the Jude Creek Earthflow, was used as a control site for the analysis of earthflow velocity from vegetation disturbance in this study. The study sites were selected after an aerial photo reconnaissance of the Willamette National Forest and ground checking of possible sites. All of the earthflows selected enter stream channels at angles of approximately 90^{o}, and constrict the valley floor along the earthflow toe. The earthflows range in size and in drainage area of the stream flowing past the earthflow toe (Table 2).

The Lookout Creek earthflow (LOC) and Jude Creek earthflow sites were chosen because of the available record of earthflow movement compiled by PNW Research Station project 4302. Monitoring of LOC began in 1974, and has established that the lower part of the earthflow has moved approximately 0.1 m./yr. (Fig. 7). The Jude Creek earthflow can be divided into three portions with different movement rates. The upper portion has an average velocity of 0.8 m./yr., the middle portion approximately 5 m./yr., and the toe has an average velocity of 11 m/yr. for the period of observation (Fig. 8). Monitoring of the upper two portions of the Jude Creek earthflow began in 1982; monitoring of the toe began in 1984. Earthflow monitoring involves recording survey-line movement, extensiometers and, for LOC, inclinometer tubes (G. Lienkaemper, pers. comm.).

The Lookout Creek earthflow is located within the H.J. Andrews Experimental Forest as is the Lower Lookout Creek earthflow (LLC) (Fig. 9). Mazama Ash was found in depressions on the surface of the presently inactive Lower Lookout Creek earthflow (LLC) indicating that the present topography was developing at least 7000 yrs ago (Swanson and James, 1975).

The French Pete Creek (FPC; Fig. 10), the Landes Creek (LAN; Fig. 11) , and the Middle Santiam Research Natural Area (RNA; Fig. 12) earthflows have no measured record of movement. A five year old road crossing LAN has been displaced about one centimeter by earthflow movement indicating that the earthflow is recently and perhaps currently active. The RNA and Jude Creek sites are two of the 25 active slump earthflows mapped by Hicks (1982) in a portion of the Middle Santiam Drainage.

EARTHFLOW NAME	DRAINAGE AREA (sq. km.)	EARTHFLOW AREA (hectares)	EARTHFLOW TOE LENGTH (meters)	EARTHFLOW VELOCITY (m/yr)	YEARS OF RECORD	EARTHFLOW CONSTRICTION RATIO (vel./width)*100	MANAGEMENT HISTORY
MIDDLE SANTIAM RNA (RNA)	184	90.7	1130	0.63	estimated	1.7	No logging or roads
JUDE CREEK	9	29.5	—	0.5 - 10	5	200.0	logging and roads
LOOKOUT CREEK (LOC)	10	17.0	313	0.1	10	1.1	logging and roads
LOWER LOOKOUT CREEK (LLC)	52	100.0	1090	0.01	estimated	0.1	extensive logging, roads
FRENCH PETE CREEK (FPC)	79	28.7	410	0.13	estimated	0.4	No logging or roads
LANCES CREEK (LAN)	96	205.0	660	1.67	estimated	6.7	extensive logging, roads

Table 2 - Characteristics of the five primary study sites, and the Jude Creek Earthflow.

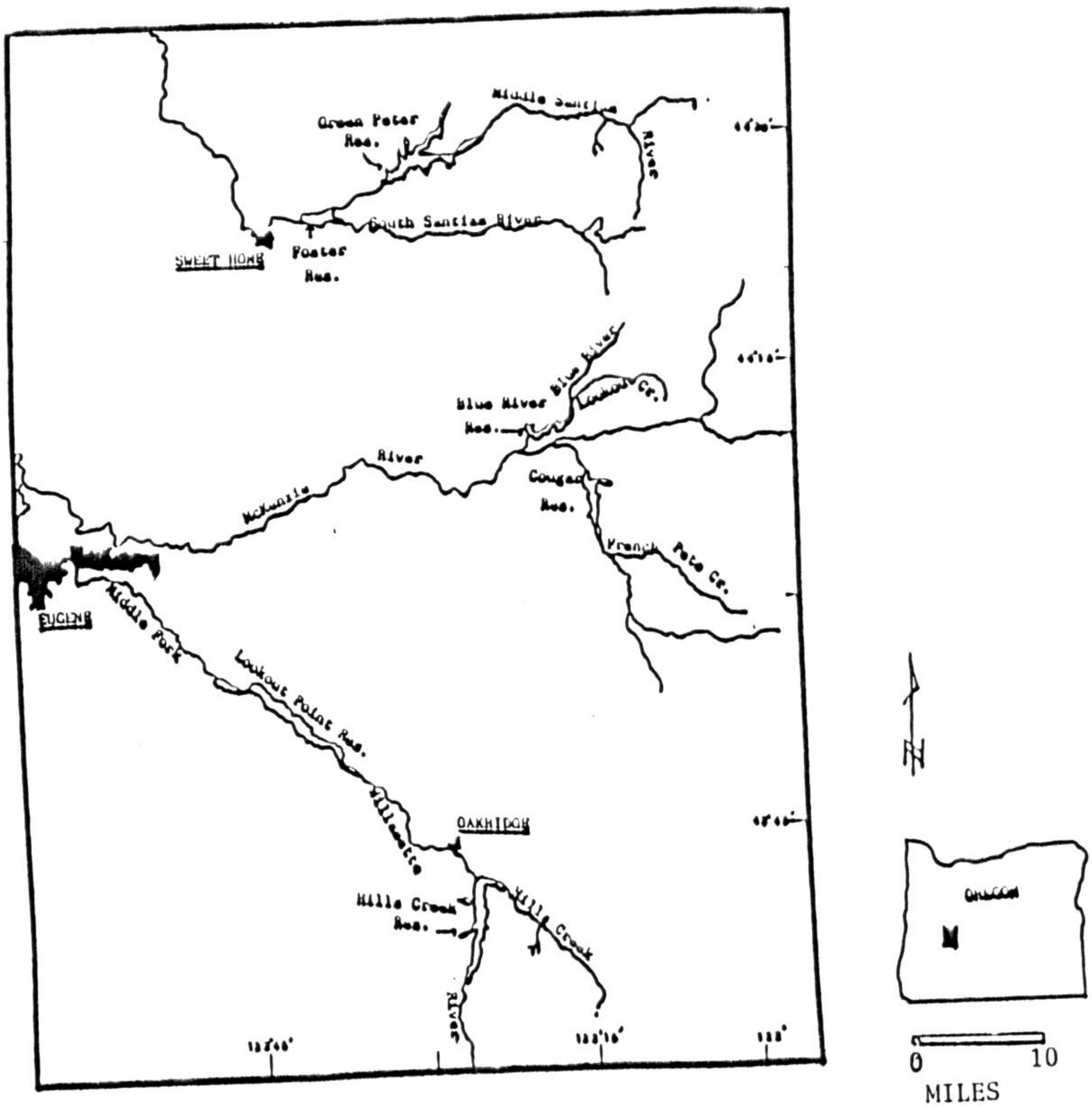

Figure 6 - Location Map.

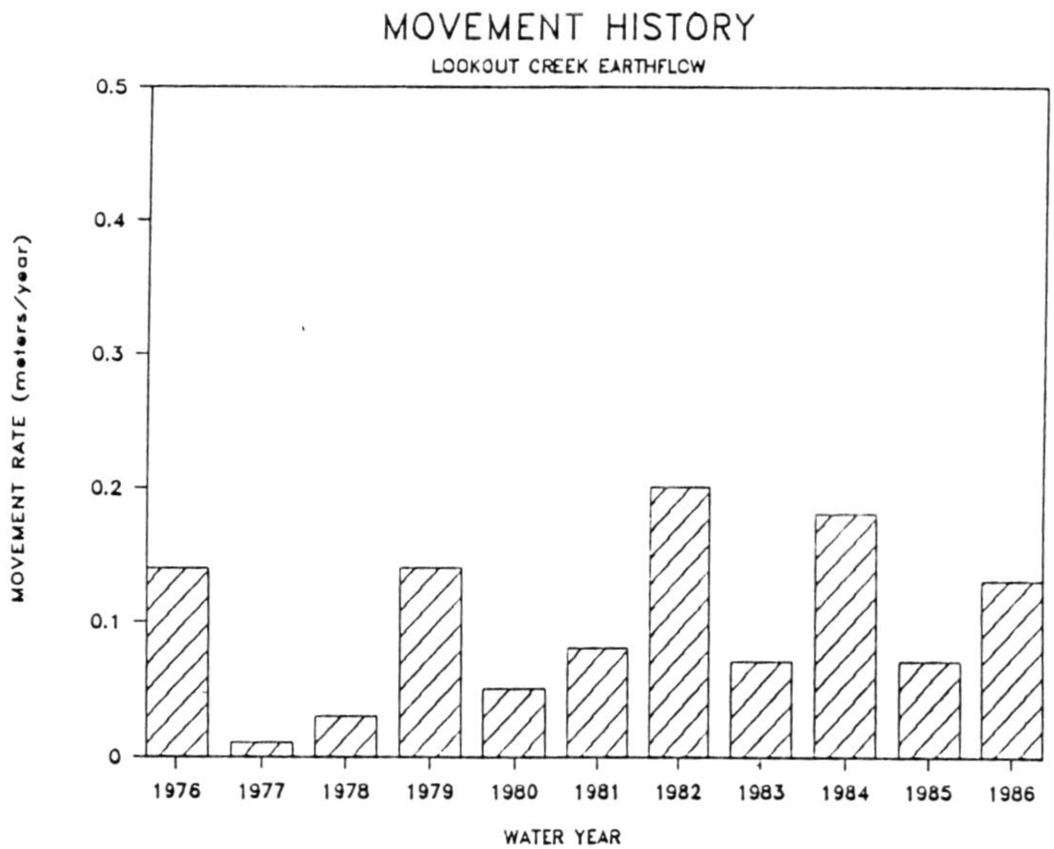

Figure 7 - Yearly movement record of the Lookout Creek earthflow.

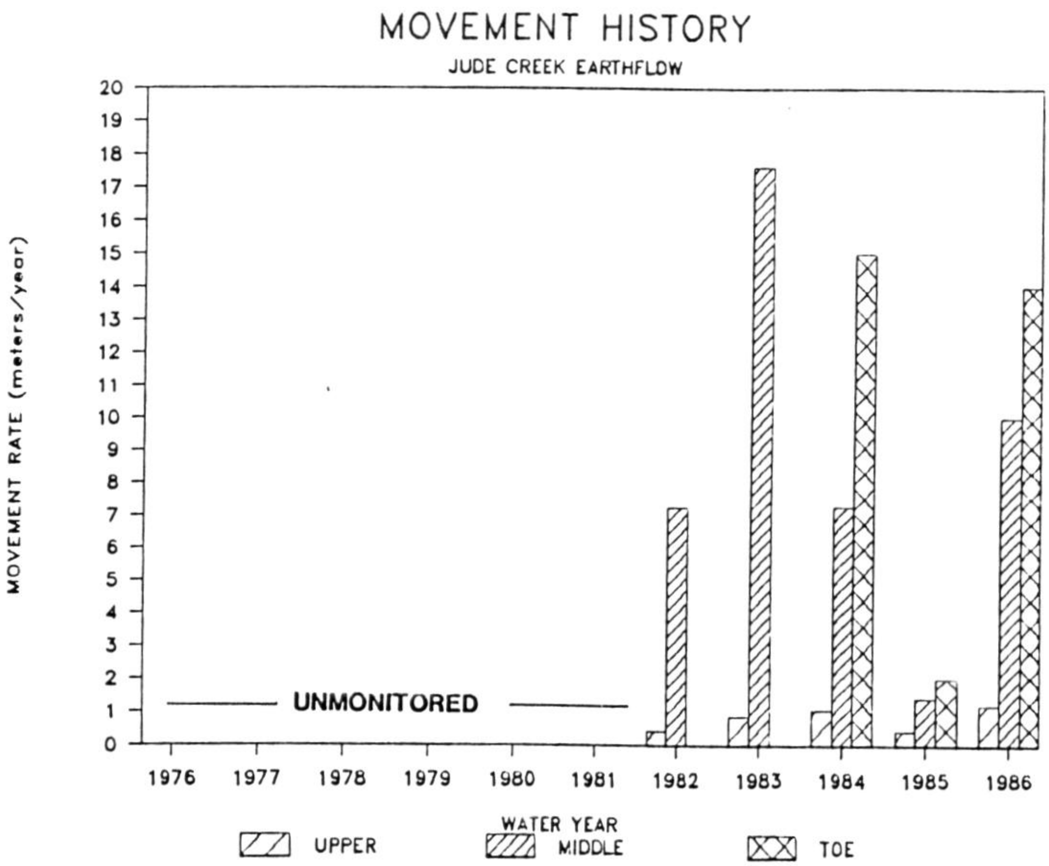

Figure 8 - Yearly movement records of Jude Creek earthflow.

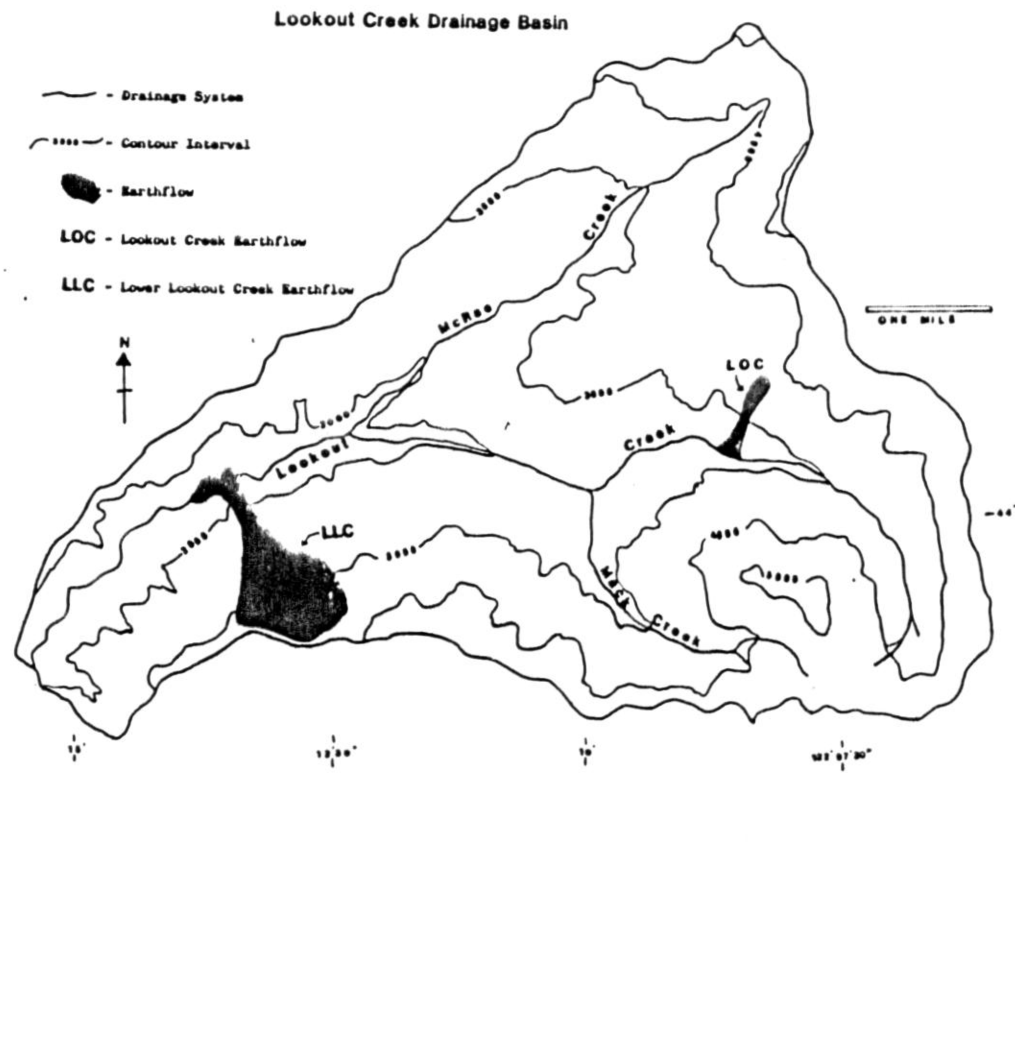

Figure 9 - The Lookout Creek drainage basin and locations of Lookout Creek (LOC) and Lower Lookout Creek (LLC) earthflows.

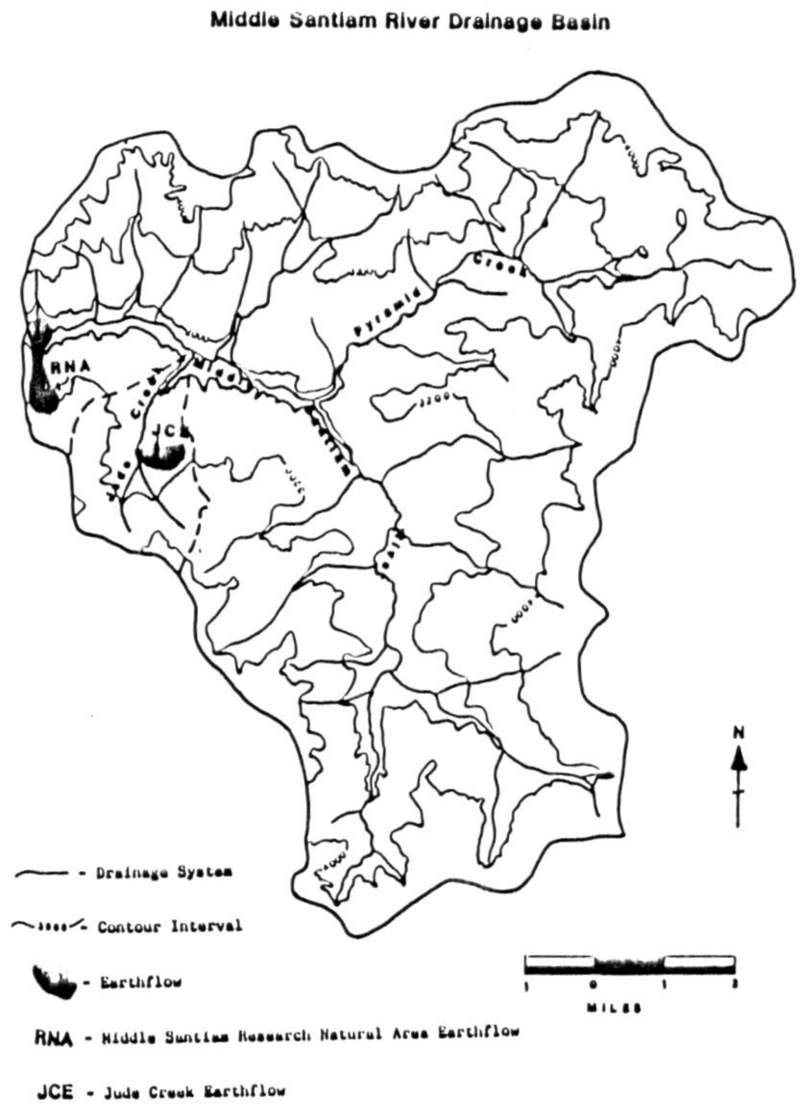

Figure 12 - The Middle Santiam River drainage basin, upstream from the Middle Santiam Research Natural Area, and the earthflow there (RNA). Also the location of the Jude Creek earthflow (JCE).

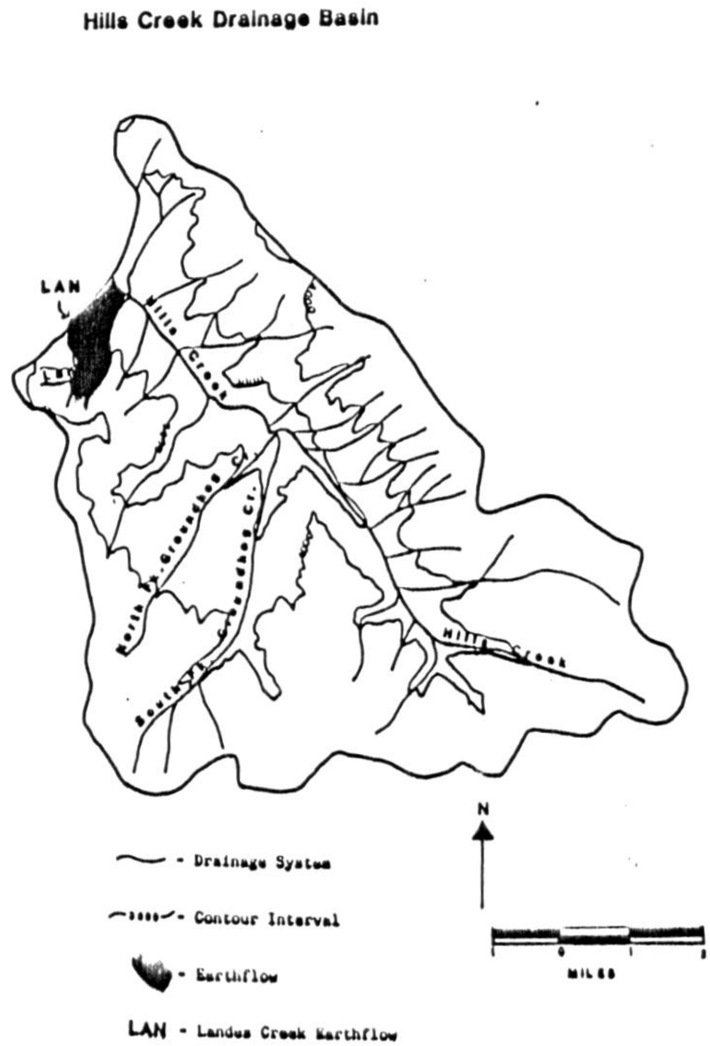

Figure 11 - The Hills Creek drainage basin, upstream from Landes Creek earthflow, and the location of the Landes Creek earthflow (LAN).

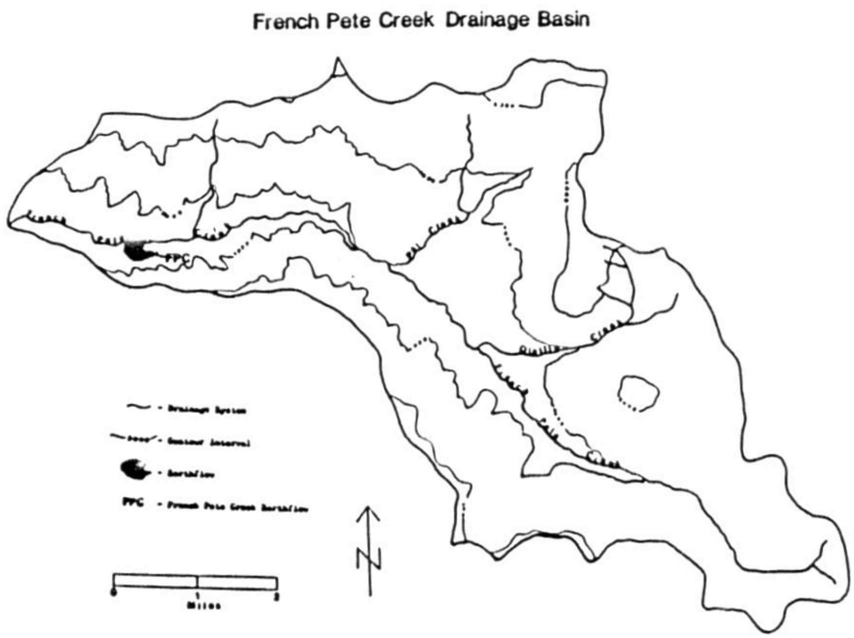

Figure 10 - The French Pete Creek drainage basin and location of French Pete Creek Earthflow (FPC).

CLIMATE

The climate of the western Cascades is dominated by wet winter months and warm, dry summers. Annual precipitation ranges from 1700 to 2600 mm/yr with most of the precipitation falling as rain from October to March (Grant, 1986). The study sites are located in the transient snow zone found between 400 and 1200 m. elevation (Harr, 1981) where snow accumulates and melts several times each year. Most large floods in the region are associated with rain on snow events which cause rapid snow melt in the transient snow zone (Harr, 1981).

VEGETATION

The five study sites are located within the *Tsuga heterophylla* zone of the Douglas Fir Region (Franklin, 1979). The dominant species supported on the hillslopes and the older terraces is Douglas Fir (*Pseudotsuga menziesii*). The primary successional species are western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*). The near-stream environment is dominated by deciduous species such as red alder (*Alnus rubra*) and big-leaf maple (*Acer macrophyllum*), which are often pioneer species after disturbances such as landslides, debris flows, and fluvial resetting of near-stream surfaces. Except for clearcuts, salvage logging, and roads less than 40 years in age foresest on these study sites are natural, post-wildfire stands ranging in age from about 100 to 500 years in age.

<u>GEOLOGY</u>

The study sites are within the physiographic province of the western Cascade Range in areas underlain by volcanic rocks of the Little Butte and Sardine Formations. The Little Butte Fm. ranges in age from Oligocene to Early Miocene, and the Sardine Fm. is Middle to Late Miocene in age (Peck <u>et</u>. <u>al</u>.,1964). The Little Butte Fm. (Peck <u>et</u>. <u>al</u>.,1964) consists of two parts: a lower sequence consisting of andesitic and dacitic flows, flow breccia, and coarse agglomerate and an upper sequence of mostly fine-grained siliceous tuffs. Swanson and James (1975) describe the Little Butte Fm. in the Lookout Creek basin as mudflows, pumice deficient pyroclastic flows, blocky breccias, and interbedded tuffaceous siltstones. Hicks (1982) described the Little Butte Fm. in the Middle Santiam drainage as a composite of andesite flows, basalt flows, lapilli tuffs, laharic breccias, pyroclastic breccias, welded tuffs, and bedded tuffs.

The Sardine Fm. (Peck <u>et</u>. <u>al</u>, 1964) consists of the Fern Ridge Tuffs, the Sardine Series, and the Upper Breitenbush Series primarily containing flows, flow breccia, tuff-breccia and conglomerate. Pliocene andesite and basalt flows cap ridges in the area (Peck <u>et</u>. <u>al</u>, 1964; Swanson and James, 1975; Hicks, 1982).

Extensive weathering and alteration of volcanic rocks has led to widespread slope instability. Swanson and James (1975) noted that greater numbers of mass-wasting events occur on the more highly weathered volcaniclasitic rocks, and that large head scarps form at the contact between the highly weathered rocks and the overlying, more competent Pliocene flows. Different volcanic units weather differently, producing a wide range of particle sizes from large boulders to clay and silt. Residual soils derived from the lava flows and intrusive bodies tend to be sand-gravel mixtures less than 3 meters deep (Hicks, 1982). Pyroclastic rocks tend to have a deeper residual soil with higher clay contents (Hicks, 1982). Areas with high smectite clay contents have a greater tendency to shear due to swelling characteristics of the clay (Hicks, 1982).

CHAPTER 2

EARTHFLOW - VEGETATION DISTURBANCE RELATIONSHIPS

Chronic earthflow movement disturbs the earthflow surface and the vegetation on it. The rotation of the root masses of trees causes development of tipped and bowed trunks that are often used as indications of mass-movement. Material is eroded from earthflow surfaces by gully erosion and by landsliding or slumping from the toe.

There are a variety of techniques which use vegetation to interpret earthflow movement, including dendrochronologic (Alestalo, 1971; Shroder, 1978; Agard, 1979; Braam et. al., 1987), tree form analysis, and stand structure and composition. The dendrochronologic techniques, which use eccentric growth of tree rings are the best quantitative developed, except for techniques involving split trees (Shroder, 1978). Dendrochronologic studies give the timing of movement and can provide an understanding about the type of movement (episodic or chronic); however, eccentricity studies do not give any information about the amount or rate of movement.

For this study we wished to estimate earthflow velocities of four of the five earthflows indirectly, since direct measurement had only been made at LOC and the record there is short. Indices of stem deformation were designed for estimating earthflow velocity. This analysis is based on the assumption that faster earthflow movement results in greater disruption of the structure of individual and groups of trees (stands), and greater range of tree age classes and species. The indices include the form and lean of stems, and the stem density of stands on the movement site. Four stem form classes were used (Fig. 13): 1)straight, 2) top curved away from the vertical, 3) bottom curved with correction to the vertical, and 4) complex. The straight form class is broken into two classes: 1A) straight with lean $<5^{o}$, and 1B) straight with lean $>5^{o}$. These form classes have different implications in terms of the timing and extent of disturbance and recovery (Table 3).

Rapid earthflows are hypothesized to have a large percentage of stems with large leans, since the rate of deformation exceeds the rate of recovery. Low velocity earthflows are expected to have fewer deformed and complex trees. Tipped, straight trees and trees leaning away from the vertical may indicate recent movement of previously straight trees which have had insufficient time to correct their growth form back to vertical. Undeformed stems may occur away from areas of movement or in areas of a flat sliding surface where there is no change in tilt of the ground surface. Complex tree form indicates episodic movement, correction, and retilting of the stem or movement over an irregular failure surface, which causes changes in direction of surface displacement even for a uniform rate of movement.

Earthflows with complex movement histories are expected to have stands with a greater range of stem forms that vary among age classes of trees. The oldest trees give the longest record of movement; form of younger trees indicate more recent movement.

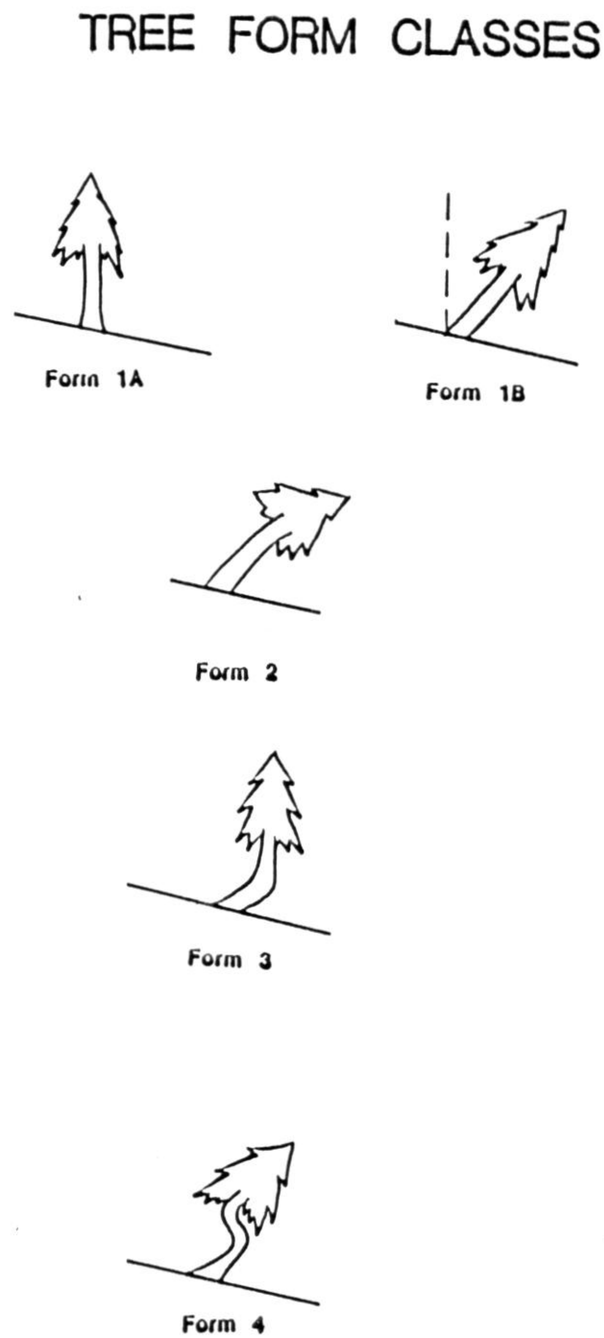

Figure 13 - Representation of the four stem classes. 1A) straight with lean less than 5°. 1B) straight with lean greater than 5°. 2) top curved away from vertical. 3) Bottom curved away from vertical. 4) complex.

FORM CLASS	FORM NUMBER	MOVEMENT RECORD
STRAIGHT, NO LEAN	1A	No movement large enough to cause tipping.
STRAIGHT W/LEAN	1B	Tipping without recovery to vertical.
TOP CURVED	2	Tipping, mass of crown causes lean away from vertical, recovery is incomplete.
BOTTOM CURVED	3	Tipping away from vertical. Recovery of the crown to vertical or near vertical by the formation of reaction wood.
COMPLEX	4	Multiple periods of tipping and recovery. Complex reaction wood patterns. Some of the "S" shape pattern may be due to overcorrection of the stems causing tipping in the opposite direction (Alestalo,1971).

Table 3 - Stem form indices and their hypothesized movement histories.

Earthflow movement may also cause changes in stand structure and stem density. As earthflow movement tilts large trees, they become more susceptible to windthrow which produces canopy openings, allowing for rapid growth of understory trees. This may decrease stem density of large trees while increasing the density of small stems. High rates of movement lead to complete collapse of the conifer canopy. As bare mineral soil is exposed by root throw and distention of the ground surface, pioneer species, such as red alder, may colonize the site, causing an increase in stem density.

Inclination of tree trunks on steep hillslopes may be caused by factors other than slope movement, such as damage by falling trees and response to gaps in the light. Inclination caused by mass movement may be larger than that of other processes, and will affect a larger area of the hillslope and larger population of trees. All of these factors considered, we expect a general positive relationship between mean lean of trees in a stand and earthflow movement rate.

FIELD PROCEDURE

Due to the dense forest cover and slow movement at most sites (average = 0.1 to 10 m/yr), earthflow-movement rates could not be determined from aerial photos as was done by Crandell and Varnes (1961), Kelsey (1977), and Iverson (1984). In order to estimate earthflow velocity, vegetation disruption as indicated by lean, deformation of trees, and stand density were quantified at sites of known earthflow velocity, for use as indices of movement rate. Five sites, three on the Jude Creek earthflow, one on the Lookout Creek earthflow, and one on a stable, non-moving site were used to develop a relationship between movement rates and vegetation disruption. The three sites located on the Jude Creek earthflow span the range of velocities of 10 - 15 m/yr, 1-5 m/yr, and 0.5 - 1.0 m/yr for the five years of record (Fig. 8). Lookout Creek earthflow has an average velocity of 0.1 m/yr for the eleven years of record (Fig. 7). The fifth site was on a non-earthflow site near Lookout Creek earthflow.

At each sampling site a transect was established and a swath of 15 meters on either side was marked. All trees which had a DBH (diameter at breast height) greater than 10 cm were sampled. Each tree was identified as to species, DBH, trunk lean, and trunk form. Trunk lean was measured in degrees from vertical by placing a Brunton compass on the uplean side of the trunk. The lean was measured at breast height. Each tree was placed into one of five trunk deformation categories (Fig. 13). After the data collection, form-1b was distinguished as all form-1 stems with leans greater than 5^{o}, and form-1A as all form-1 stems with lean less than 5^{o}.

DBH classes were also established after data collection as a separate classification, and also as a possible relative age classification. The DBH classifications are DBH <30 cm, DBH 30-49 cm, DBH 50-80 cm, and DBH >80 cm.

Stem density was determined for each site by dividing the number of stems by the plot area. For the sites with multiple plots the total number of stems and the total plot area were used.

Trees growing on earthflows of unknown velocities were sampled in the same way. On Landes Creek earthflow transects were placed in areas which were not disturbed by road building or logging operations. Trees were not sampled on Lower Lookout Creek earthflow since this area has been thoroughly disturbed by clearcutting and salvage-logging operations. Salvage logging compromises use of these techniques, since trees of irregular growth may be selectively removed.

RESULTS

Form Class

Certain form classes are more common on sites which have higher velocities. There is a higher percent of total stems in forms 1B and 3 on sites with higher velocity (Figs. 14 and 15). Also, there is a general increase in the percentage of form-1A trees for earthflows with lower velocity. Form-1B is more indicative of recent movement since correction has yet to visibly occur than the present rate of movement. Form-3, on the other hand, indicates that trees have made some recovery to vertical.

All four form classes are found at each site, and each site has stems of each form in each DBH class although not all sites have the same relative abundance of form classes. This is due to differences in the age of stands and earthflow histories. Both FPC and Jude Creek toe areas have very few, if any, stems greater than 80 cm DBH (Table 4). For FPC the wildfire history has precluded development

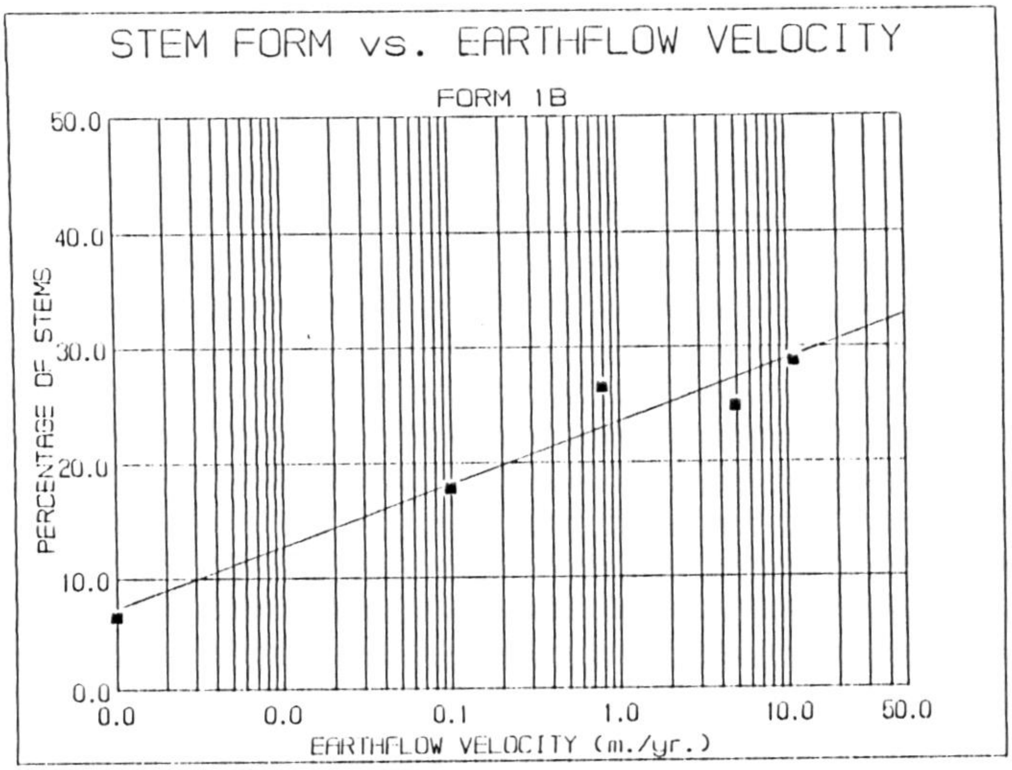

Figure 14 - Logarithmic relationship between earthflow velocity and stem form 1B (straight with lean > 5^{o}).

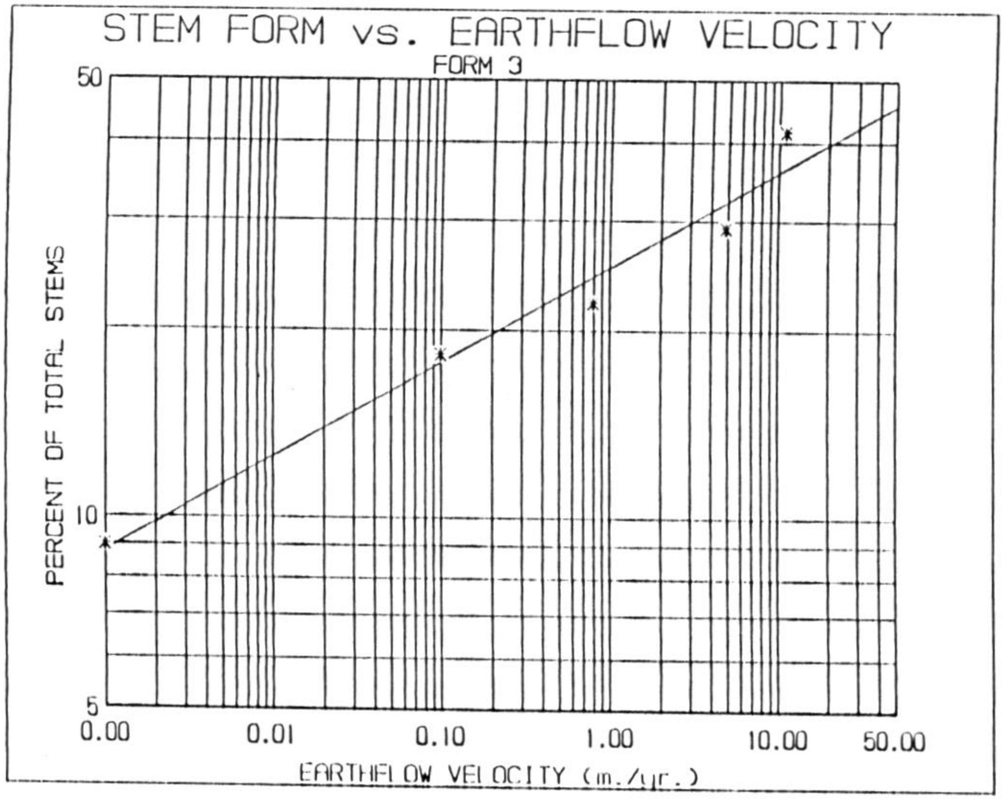

Figure 15 - Logarithmic relationship between earthflow velocity and stem form 3 (bottom curved, top approaches vertical).

	SITES WITH MEASURED VELOCITY					UNMONITORED SITES		
	JUDE CR. TOE	JUDE CR. MIDDLE	JUDE CR. UPPER	LOOKOUT CREEK	STABLE SITE	HNA	LAN	FFC
NUMBER SAMPLED TREES	38	52	45	302	89	102	90	92
STEM DENSITY (stems/m^2)	0.061	0.041	0.05	0.04	0.039	0.041	0.052	0.102
NUMBER OF PLOTS	1	1	1	6	2	2	2	1
PERCENT OF TOTAL STEMS BY SPECIES								
% CEDAR	5.3	9.8	15.6	56.9	22.5	7.8	24.4	25.0
% DOUG FIR	10.5	84.3	77.8	33.6	20.2	86.3	66.7	73.9
% HEMLOCK	0.0	0.0	0.0	6.6	57.3	0.0	7.8	1.1
% ALDER	76.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% MAPLE	7.9	0.0	0.0	3.0	0.0	0.0	0.0	0.0
% OTHER	0.0	5.9	6.7	0.0	0.0	5.9	1.1	0.0
PERCENT OF TOTAL STEMS BY FORM CLASS								
% FORM 1	0.0	19.2	22.2	20.2	61.8	27.5	31.1	35.9
% FORM 1B	28.9	25.0	26.7	17.9	6.7	17.6	7.7	9.8
% FORM 2	5.5	9.8	15.6	25.2	14.6	5.9	16.6	18.7
% FORM 3	41.7	29.4	22.2	18.3	9.0	25.5	30.0	13.2
% FORM 4	25.0	15.7	13.3	18.3	7.9	23.5	15.6	22.0
PERCENT OF TOTAL STEMS BY DBH								
% DBH <30	83.8	47.1	60.0	43.5	46.1	43.3	50.0	66.3
% DBH 30 50	8.1	15.7	13.3	22.9	18.0	12.4	21.1	18.5
% DBH 50 80	8.1	25.5	8.9	17.3	14.6	14.4	16.7	14.1
% DBH >80	0.0	11.8	17.9	16.3	21.4	29.9	12.2	1.1
MEAN TREE LEAN (°)	15.64	15.91	7.25	6.65	1.35	7.11	8.07	5.76
STD.ERROR	1.57	1.88	0.83	0.57	0.57	0.6	1.53	0.55

Table 4 - Summary of vegetation characteristics for all sites, including sites of unmeasured velocity.

of old, large trees, while the extremely rapid movement at Jude Creek is the reason why so few large trees are present.

Lean

The mean lean of all trees sampled at each site (Table 4) is strongly related to measured earthflow velocity (Fig. 16). Trees on faster sites have greater mean leans.

The mean lean of stems in each form class is also related to velocity (Table 5). The form-1A stems have the lowest lean, as expected by definition. Form-2 stems have the next lowest leans. Forms 1B, 3, and 4 have similar leans, with the lean of form class 1B consistently higher than the other two form classes. Generally, the mean leans of these three form classes increase with increased velocity.

Stem Density and Stand Structure

Stem density varies from 0.04 to 0.06 stems/m^2 (Table 4). Stem density appears to increase somewhat with an increase in velocity; however, a true correlation cannot be made. There is very little variation in the stem density among the upper two sites at Jude Creek, the stable site, and the Lookout Creek site. The toe site of Jude Creek has a significantly greater stem density and the vegetation is primarily deciduous while the other sampled sites are primarily coniferous. In order to determine if there is truly an increase in stem density with an increase in velocity above 5 m/yr additional high velocity earthflow sites should be added to the database. The same is true in order to determine if there is really

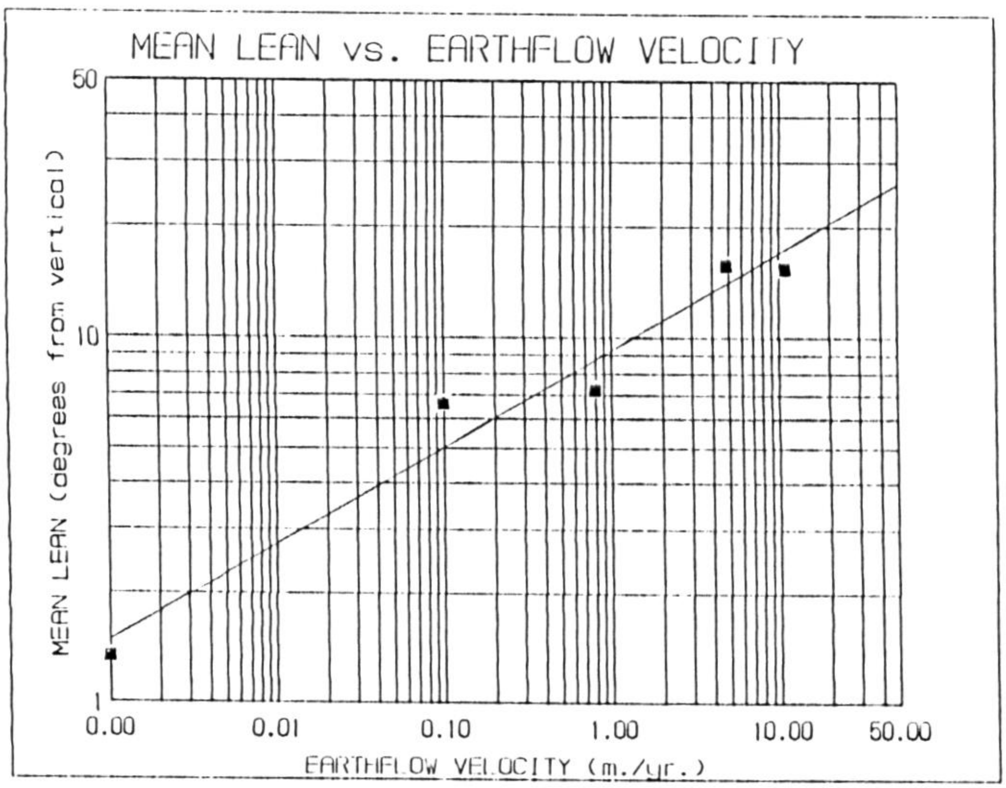

Figure 16 - Logarithmic relationship between earthflow velocity and the mean lean for each sampled stand.

MEAN LEAN OF EACH FORM CLASS FOR MONITORED SITES					
	LOOKOUT CR E.F.	JUDE CREEK - UPPER	JUDE CREEK - MIDDLE	JUDE CREEK - TOE	LOOKOUT-STABLE
FORM 1	2.11	2.50	1.90	-.-	0.00
FORM 1B	13.31	9.00	24.46	19.00	7.17
FORM 2	5.50	6.83	10.00	17.50	2.00
FORM 3	8.02	10.20	17.27	12.14	3.88
FORM 4	5.33	7.17	21.38	16.56	3.43
MEAN FOR ALL FORMS	6.64	7.25	16.02	15.22	1.35

Table 5 - The mean lean of each form class for the sites of measured velocities.

a velocity threshold at which stands change from primarily coniferous to primarily deciduous.

DISCUSSION

Three relationships are useful in estimating earthflow velocity at sites where velocity has not been monitored. Mean lean and percent of stems in form-3 appear to be good indicators of long term movement rate. Percent of straight trees with lean (form-1B) probably reflects recency of movement more than rate.

These three vegetation factors do not give similar estimates of velocity for earthflows without direct measurement (Table 6). The different relationships give velocities that range from millimeters per year to meters per year for the same site. The primary reason for the disagreement of velocities between relationship represents a different movement history (Table 3). The relationship between form-1B and velocity may be a better estimate of the present day velocities compared to the other two relationships. However, since we are interested in the long term movement history (decades to centuries), form-3 and mean lean offer estimates of earthflow velocity which are more appropriate. The average of the velocities estimated from the mean lean and from the form 3 relationships will be the average earthflow velocity for the three unmonitored sites used in this study.

The velocities determined using vegetation disruption indexes are relative, since the disruption being indexed is over the entire stand composed of trees ranging in age, size, and species.

SITE	FORM 1B a	FORM 3 b	LEAN c	AVERAGE a,b,+c	AVERAGE b + c
	EARTHFLOW VELOCITY (m./yr.)				
FRENCH PETE CR.	0.0034	0.15	0.11	0.09	0.13
LANDES CR.	0.0015	2.65	0.69	1.11	1.67
RES. NAT. AREA	0.09	0.95	0.30	0.45	0.63

Table 6 - Velocity estimates for the three unmonitored sites interpreted from the relationships between measures of vegetation disruption and velocity on sites with known velocity (Figs. 15, 16, and 17).

It is not known if different species react similiarly to different types of physical disturbance, or if trees of the same species, but of different ages and sizes would react differently to the same disturbance (Shroder, 1978). Also, the period of monitoring on the sites of known velocity has been less than 12 yrs, and most trees with DBH's greater than 10 cm. are much older, so it is unknown if the movement rates that deformed the present mature stand were greater, equal to, or less than the observed rates of movement. For these reasons more than one relationship should be used to estimate earthflow velocity from vegetation disturbance. Dendrochronologic analysis of split trees and trees with eccentric growth (Shroder, 1978) might help to unravel some of the complexities of the histories of earthflow movement and vegetation disruption.

CHAPTER 3

VALLEY FLOOR GEOMETRY

Movement of earthflows can greatly change valley floor geomorphology. Encroachment of an earthflow on a stream constricts the valley floor as the stream is pushed toward the opposite wall. This leaves little room for formation and maintenance of floodplains, terraces, and alluvial fans in constricted reaches. As constriction continues, deposition begins to occur in the stream reach upstream of the constriction, primarily due to channel gradient changes and hydraulic backwater effects. Increase in stored sediment in the upper reach may, over long periods of time, cause widening of the valley floor in the reach upstream of the constriction.

Three reaches were studied at each of the five study sites. The earthflow constrained reach is defined spatially by the length of the earthflow toe where it enters the stream. The lower and upper reaches are defined by their relative positions downstream and upstream of the constriction (Fig. 4b). The upper and lower reaches are contiguous to the constrained reach and were assigned arbitrary lengths in terms of channel units, generally 30 channel units in length.

To examine effects of earthflows on valley floor width, I used comparisons between the three reaches at a site and comparisons of similar reaches between sites. It is hypothesized that the valley floor within the constricted reach is the narrowest, and the valley floor of the upper reach is the widest.

FIELD METHODS

Valley floor transects were placed at intervals of 50 to 110 meters along each creek, perpendicular to the valley wall. Generally 10 to 12 transects were sampled within each reach. This sampling was done in the field at LAN, RNA, and LOC using a tape to measure width and a stadia rod to measure elevation. The width of the channel at each transect was also measured so to obtain the complete valley floor width. Cross sections were measured perpendicular to the channel flow at LOC, LAN, and RNA using a tape and stadia rod. For LLC and FPC transects were measured from maps produced in another project. The total valley floor width for a transect includes the width of the channel between the valley floors. The data collected along these transects include height of surface above low flow channel, the width of the surface, the dominant vegetation type on the surface, and the approximate age of the vegetation based on visual estimates.

Surfaces measured were less than 8 meters above the low flow channel. Also not measured were surfaces that abutted the active channel and were greater than 6 meters in height. Alluvial fans were not included in the area defined as valley floor. Inventoried valley floor surfaces are almost entirely fluvial, but may also include landslide deposits and low slump benches.

RESULTS

Valley floor width

The mean total valley floor width for each reach was divided by the mean active channel width for each reach (Table 7) to calculate a valley floor width index (Table 7; Figs. 17a-e). Another expression of this index uses the mean active channel width for the lower reach as the denominator (Table 8). The first index uses the individual reaches as their own scale, while the second index uses a standard value for each site. Differences between the two indexes represent contrasts in active channel widths between the reaches.

At all sites the valley floor of the earthflow reach is the most constricted reach. The width index of the constricted reach at LOC is wider than the other constricted reaches. This may be attributed to the extensive landsliding that has occurred at the toe in 1964 - 1965 (Swanson and Swanston, 1977). The deposits have since been partially reworked by fluvial processes, leaving some terrace-like landforms of mixed origin.

The upper reaches are considerably wider than the lower reaches at all sites. However, the width index of the upper reach at RNA is less than the lower reach at that site based on the active channel width per reach in part because the active channel width for the upper reach of RNA is substantially wider than the lower reach. The absolute valley floor widths and width indexes of upper reaches of LLC and LAN are twice those of their respective lower reaches. The upper reach of FPC is close to twice as wide as its respective lower reach (Table 7). The valley floor width of the upper reach at LOC

SITE	MEAN VALLEY FLOOR WIDTH (meters)	MEAN ACTIVE CHANNEL WIDTH - EACH REACH (meters)	MEAN VALLEY FLOOR WIDTH INDEX	STANDARD ERROR
LOOKOUT CR.-LOWER	38.3	9.4	4.09	0.16
LOOKOUT CR.-CONSTRICTED	19.1	8.4	2.28	0.24
LOOKOUT CR.-UPPER	48.0	7.5	6.43	0.68
FRENCH PETE-LOWER	53.9	20.3	2.64	0.33
FRENCH PETE-CONSTRICTED	26.9	20.2	1.33	0.28
FRENCH PETE-UPPER	90.7	18.8	4.84	0.61
LOWER LOOKOUT CR.-LOWER	49.7	18.0	2.70	0.43
LOWER LOOKOUT CR.-CONSTRICTED	30.3	19.5	1.56	0.31
LOWER LOOKOUT CR.-UPPER	157.9	27.9	5.65	0.96
LANDES CR.-LOWER	70.6	17.9	3.95	0.55
LANDES CR.-CONSTRICTED	30.7	16.7	1.84	0.22
LANDES CR.-UPPER	203.4	22.6	8.98	1.09
RES.NAT.AREA-LOWER	88.8	27.9	3.19	0.59
RES.NAT.AREA-CONSTRICTED	43.8	28.5	1.54	0.16
RES.NAT.AREA-UPPER	141.8	35.1	4.04	0.47

Table 7 - The valley floor width index - valley floor width divided by the mean active channel width for each reach.

SITE	MEAN VALLEY FLOOR WIDTH (meters)	MEAN ACTIVE CHANNEL WIDTH - LOWER REACH (meters)	MEAN VALLEY FLOOR WIDTH INDEX	STANDARD ERROR
LOOKOUT CR.-LOWER	38.3	9.4	4.09	0.16
LOOKOUT CR.-CONSTRICTED	19.1	9.4	2.04	0.32
LOOKOUT CR.-UPPER	48.0	9.4	5.13	0.54
FRENCH PETE-LOWER	53.9	20.3	2.64	0.33
FRENCH PETE-CONSTRICTED	26.9	20.3	1.33	0.27
FRENCH PETE-UPPER	90.7	20.3	4.48	0.56
LOWER LOOKOUT CR.-LOWER	49.7	18.0	2.70	0.43
LOWER LOOKOUT CR.-CONSTRICTED	30.3	18.0	1.69	0.34
LOWER LOOKOUT CR.-UPPER	157.9	18.0	8.78	1.50
LANDES CR.-LOWER	70.6	17.9	3.95	0.55
LANDES CR.-CONSTRICTED	30.7	17.9	1.72	0.20
LANDES CR.-UPPER	203.4	17.9	11.38	1.39
RES.NAT.AREA-LOWER	88.8	27.9	3.19	0.59
RES.NAT.AREA-CONSTRICTED	43.8	27.9	1.57	0.16
RES.NAT.AREA-UPPER	141.8	27.9	5.09	0.59

Table 8 - The valley floor width divided by the mean active channel width of the lower reach.

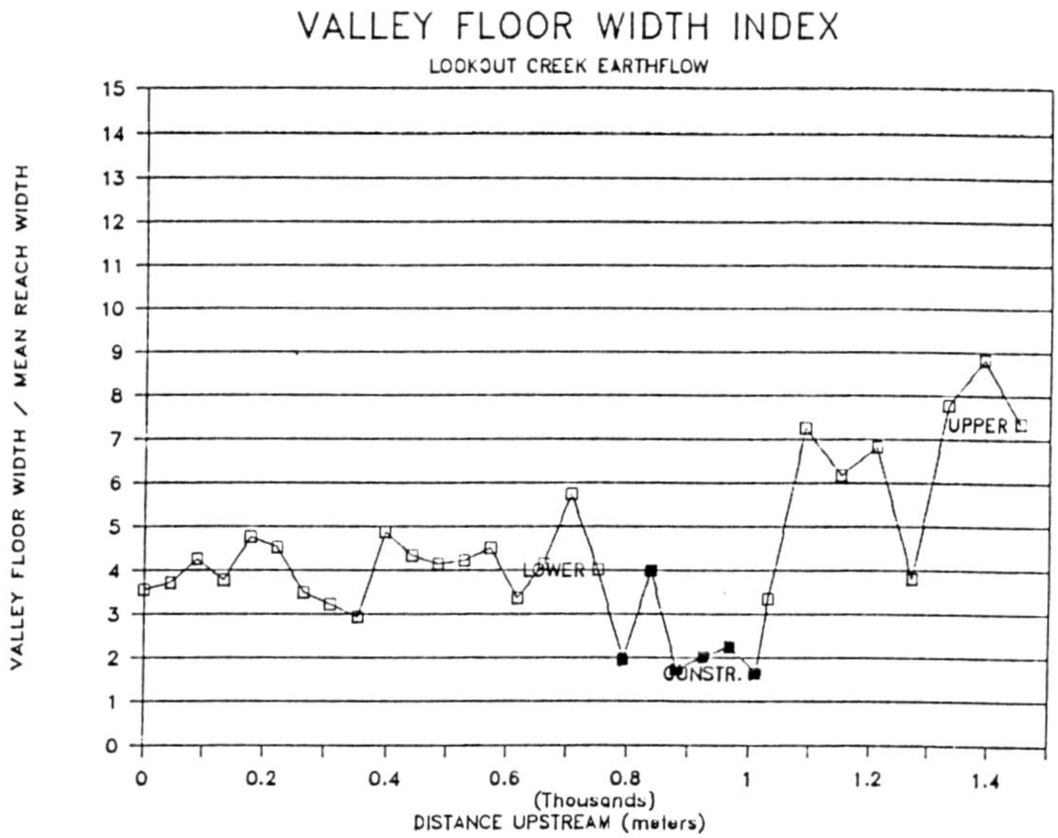

Figure 17a - The valley floor width indices of the Lookout Creek Earthflow (LOC).

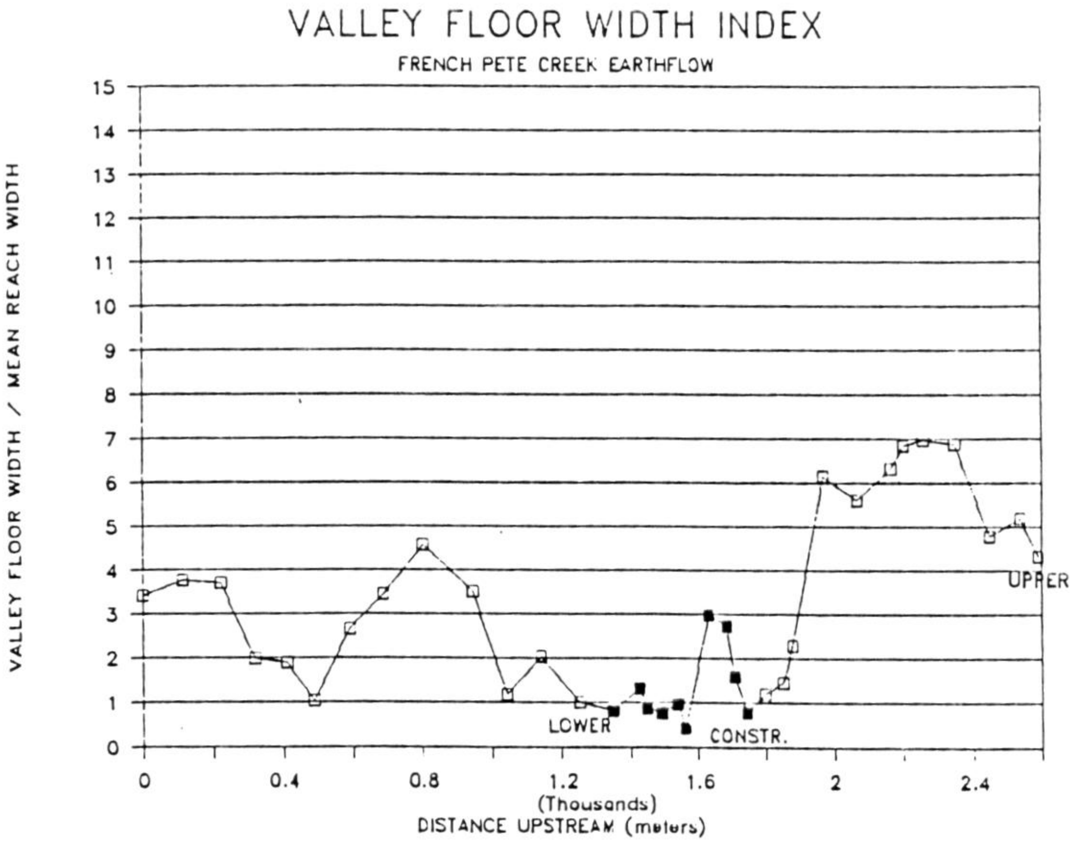

Figure 17b - The valley floor width indices of the French Pete Creek Earthflow (FPC).

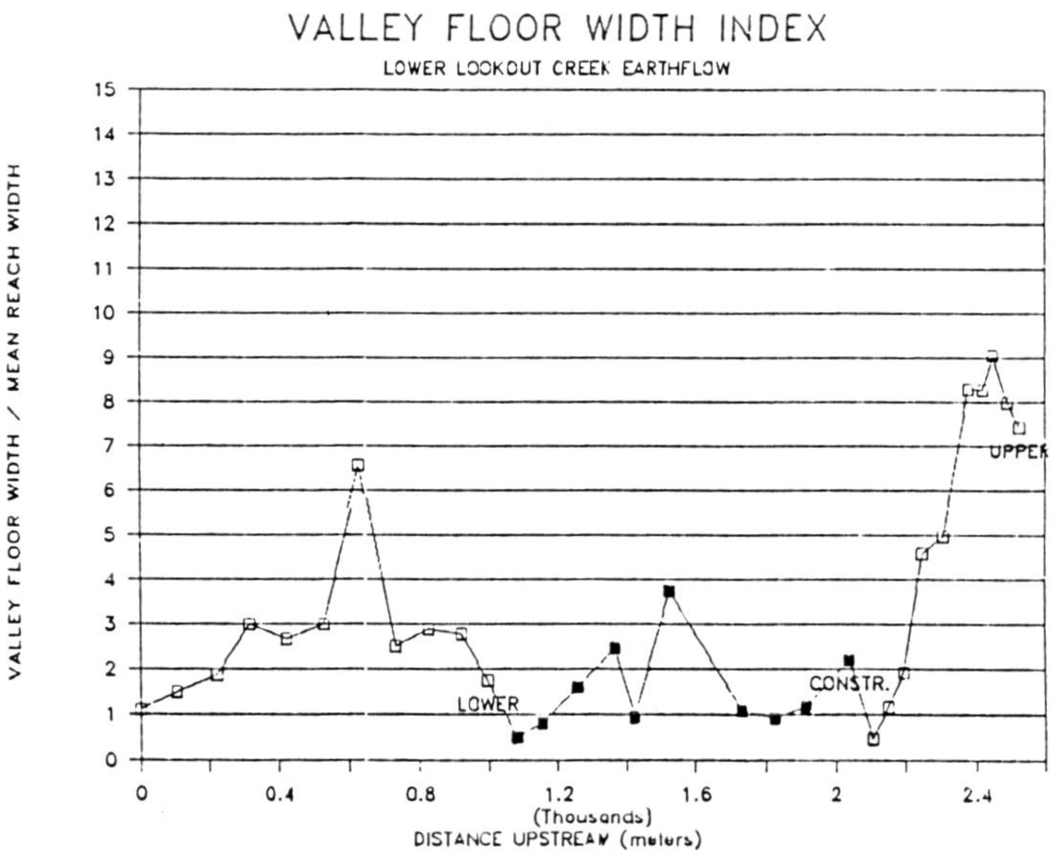

Figure 17c - The valley floor width indices of the Lower Lookout Creek Earthflow (LLC).

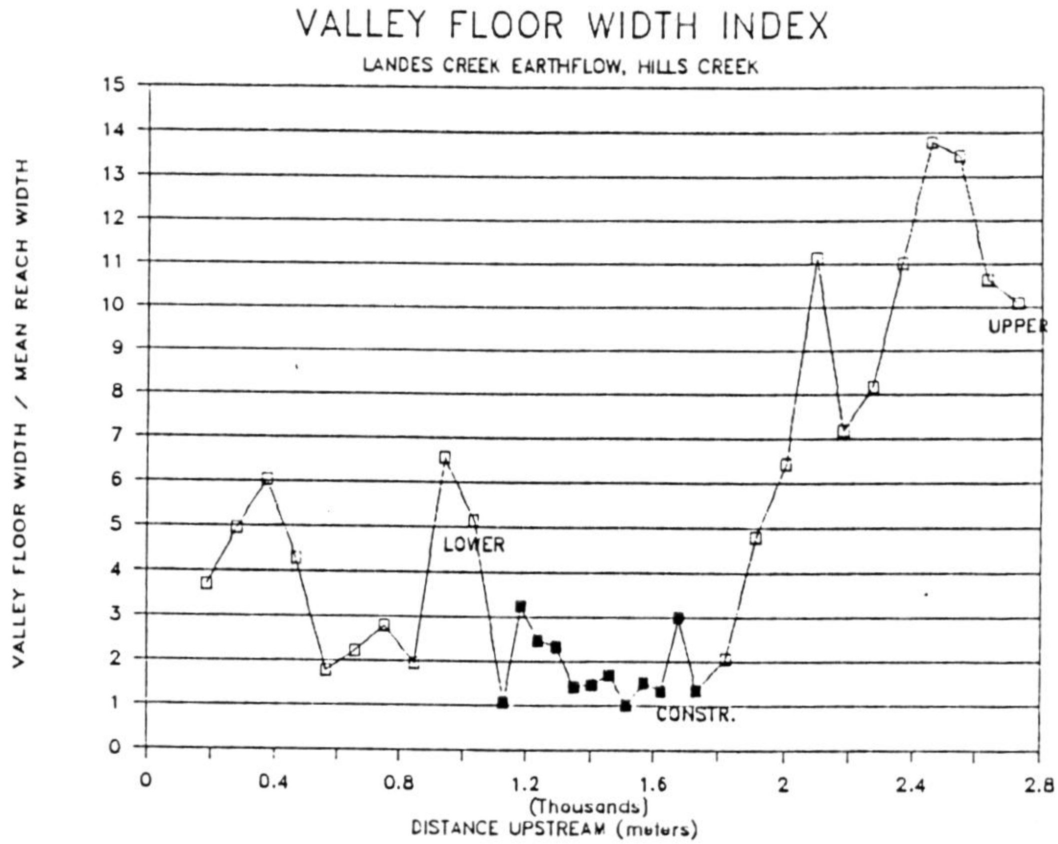

Figure 17d - The valley floor width indices of the Landes Creek Earthflow (LAN).

is only slightly greater than its lower reach, which could be due, in part, to the steep slope (0.05-0.07) of the channel at the study site. This gradient may be a limiting factor in the development of extensive depositional surfaces in the upper reach.

These wide, unconstrained reaches, common upstream from the constricted reaches, are also termed flats where the valley floors are very wide and have a low gradient compared to the surrounding reaches. The area sampled as the upper reaches at LLC, LAN, and FPC include the transition from the constricted reach to the flat, and contain only portions of the flats (Table 9; Fig. 18). The sampled upper reach of RNA contains the whole flat, as well as part of a bedrock constricted area in the upstream portion of the sampled reach (Table 9; Fig. 18).

Although each reach has variation in valley floor width (Figs. 17a-e), there is, in general, a low standard error for the mean valley floor width index at each reach (Table 7). In general the earthflow constricted reaches have the lowest variation in valley floor width index and the upper reaches have the greatest variation.

The range of elevations of floodplains and terrace surfaces in each reach is variable. In the constrained reaches very few fluvial surfaces occur beyond the active channel surfaces, and those that are present are very narrow (Table 10). Greater than 50% of the sampled valley floor width in the constricted reach is active channel surfaces. In general the elevation classes of terraces and floodplains in the lower reach are present in the upper reach. However, surfaces in the upper reach are wider

EARTHFLOW	UPPER REACH LENGTH (km.)	TOTAL FLAT LENGTH (km.)	% FLAT SAMPLED
LOWER LOOKOUT CREEK	0.64	3.50	18.29
LANDES CREEK	1.03	2.76	37.32
FRENCH PETE CREEK	0.95	1.02	93.14
RESEARCH NATURAL AREA	1.76	0.87	100.00
LOOKOUT CREEK		NO DISTINCT FLAT	

Table 9 - Length of broad, earthflow-created unconstrained upstream reach (valley flat) and length of flat sampled.

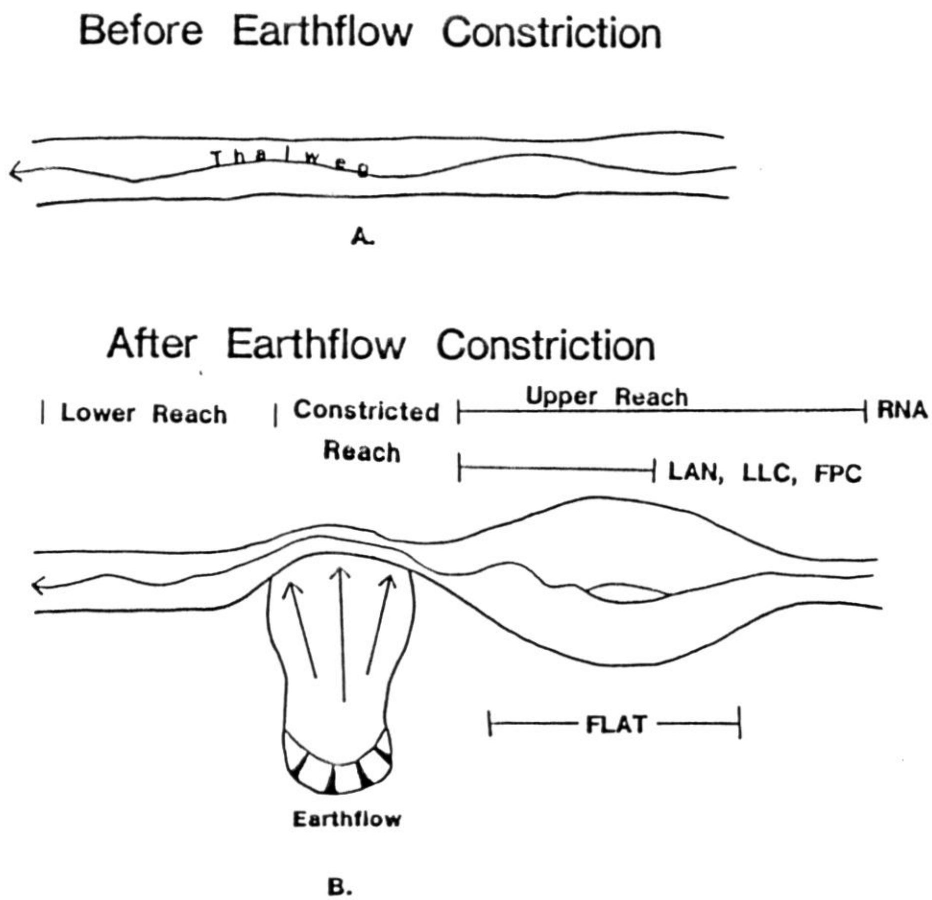

Figure 18 - Schematic representation of A) the valley floor before earthflow constriction, and B) after earthflow constriction with the formation of a flat in the upper reach. The relative length of the upper reach sampled at each site is also shown.

REACH	TRANSECT DISTANCE IN EACH ELEVATION CLASS (meters) ACT.CHAN	1-2 m.	2-3 m.	3-4 m.	4-5 m.	>5 m.	TOTAL LENGTH	NUMBER OF TRANSECTS
LOOKOUT CREEK EARTHFLOW								
LOWER	305.1	162.2	115.9	66.9	23.8	25.9	699.8	18
CONSTRICTED	87.7	0.0	5.2	21.6	0.0	0.0	114.5	6
UPPER	148.1	82.5	39.6	70.9	43.0	0.0	384.1	8
FRENCH PETE CREEK EARTHFLOW								
LOWER	294.4	141.8	111.9	28.9	18.0	99.0	694.0	11
CONSTRICTED	161.4	20.0	45.8	41.9	0.0	0.0	269.1	10
UPPER	289.6	232.6	127.7	420.1	0.0	18.0	1088.0	12
LOWER LOOKOUT CREEK EARTHFLOW								
LOWER	217.6	195.5	46.3	53.3	22.2	12.1	547.0	11
CONSTRICTED	238.3	0.0	32.3	32.5	0.0	0.0	303.1	10
UPPER	434.9	290.9	468.7	58.1	0.0	483.8	1736.4	10
LANDES CREEK EARTHFLOW								
LOWER	250.9	89.8	246.9	80.3	38.4	0.0	706.3	10
CONSTRICTED	244.6	47.0	4.4	20.0	47.6	21.9	385.5	12
UPPER	363.8	170.1	1199.3	420.9	34.5	0.0	2188.6	11
HNA EARTHFLOW								
LOWER	388.2	0.0	151.4	204.8	244.0	15.4	1003.8	11
CONSTRICTED	437.8	30.0	23.4	33.9	0.0	0.0	525.1	12
UPPER	395.6	22.5	95.6	575.8	92.0	94.5	1276.0	9

REACH	TOTAL TRANSECT LENGTH (meters)	% OF TOTAL TRANSECT LENGTH BY REACH ACT.CHAN	1-2 m.	2-3 m.	3-4 m.	4-5 m.	>5 m.
LOOKOUT CREEK EARTHFLOW							
LOWER	699.8	43.6	23.2	16.6	9.6	3.4	3.7
CONSTRICTED	114.5	76.6	0.0	4.5	18.9	0.0	0.0
UPPER	384.1	39.0	21.5	10.0	18.2	11.3	0.0
FRENCH PETE CREEK EARTHFLOW							
LOWER	694.0	42.4	20.4	16.1	4.2	2.6	14.3
CONSTRICTED	269.1	60.0	7.4	17.0	15.6	0.0	0.0
UPPER	1088.0	26.6	21.4	11.7	38.6	0.0	1.7
LOWER LOOKOUT CREEK EARTHFLOW							
LOWER	547.0	39.8	35.7	8.5	9.7	4.1	2.2
CONSTRICTED	303.1	78.6	0.0	10.7	10.7	0.0	0.0
UPPER	1736.4	25.0	16.8	27.0	3.3	0.0	27.9
LANDES CREEK EARTHFLOW							
LOWER	706.3	35.5	13.0	35.0	11.4	5.4	0.0
CONSTRICTED	385.5	63.5	12.2	1.1	5.2	12.3	5.7
UPPER	2188.6	16.6	7.8	54.8	19.2	1.6	0.0
HNA EARTHFLOW							
LOWER	1003.8	38.7	0.0	15.1	20.4	24.3	1.5
CONSTRICTED	525.1	83.4	5.7	4.5	6.5	0.0	0.0
UPPER	1276.0	31.0	1.8	7.5	45.1	7.2	7.4

Table 10 - Total transect length and percent of total transect length sampled in each valley floor surface height class, for each reach.

(Table 10). The wider upper reaches also contain more mid-channel and point bars than do the other reaches. Secondary channels are also common in the upper reach.

Valley floor width related to earthflow movement

The time it would take for the earthflow to have formed the present valley floor width in the constricted reach at each site was estimated by first determining the difference in valley floor width between the constricted reach and the other two reaches, and dividing this difference by the estimated earthflow velocities (Table 11). The result is an estimate of the time of movement of the earthflow. This analysis assumes constant earthflow velocity at rates measured or estimated for the past decade to century; this assumption is probably not accurate, but provides relative time intervals.

The time needed for the Lookout Creek earthflow to overrun a valley floor similar to the upper reach is close to 300 yrs, similar to that estimated by Swanson and Swanston (1977). They considered this a minimum estimate because valley floor width in the constricted reach may remain unchanged for long periods of time after the earthflow has crossed the valley floor. Thereafter, fluvial erosion of the toe or channel aggradation may occur in response to earthflow movement but valley floor width is unchanged.

SITE	AVERAGE VALLEY FLOOR WIDTH (meters)	AVERAGE ACTIVE CHANNEL WIDTH (meters)	ESTIMATED EARTHFLOW VELOCITY (m/yr)	VALLEY FLOOR WIDTH DIFFERERNCE (meters)	TIME (years)
LOOKOUT CR.-LOWER	38.3	9.4		19.2	190
LOOKOUT CR.-CONSTRICTED	19.1	8.4	0.10		
LOOKOUT CR.-UPPER	48.0	7.5		28.9	290
FRENCH PETE-LOWER	53.9	20.3		27.0	210
FRENCH PETE-CONSTRICTED	26.9	20.2	0.13		
FRENCH PETE-UPPER	90.7	18.8		63.8	490
LOWER LOOKOUT CR.-LOWER	49.7	18.0		19.4	1900
LOWER LOOKOUT CR.-CONSTRICTED	30.3	19.5	0.01		
LOWER LOOKOUT CR.-UPPER	157.9	27.9		127.5	1280
LANDES CR.-LOWER	70.6	17.9		39.9	25
LANDES CR.-CONSTRICTED	30.7	16.7	1.67		
LANDES CR.-UPPER	203.4	22.6		172.7	100
RES.NAT.AREA-LOWER	88.8	27.9		45.1	70
RES.NAT.AREA-CONSTRICTED	43.8	28.5	0.63		
RES.NAT.AREA-UPPER	141.8	35.1		98.0	160

Table 11 - Estimated time for earthflow to overrun the valley floor of each reach.

DISCUSSION

Variations in valley width among the three reaches are pronounced. The upstream reach is much wider than the earthflow-constricted reach and,in most cases, than the lower reach. The upstream reach widths include the transition between the constricted reach and the wider upstream valley flats that are common above constrictions (Beschta, 1983; Van Haveren et. al., 1987). At FPC, LAN, and LLC only a portion of the valley flat was sampled along with the transition zone between the two widths (Table 9), thereby explaining the relatively high standard error for the valley floor width index associated with these sites. The sampled reaches upstream of LOC and RNA included the entire valley flat, and in the case of RNA, the transition into a bedrock constriction zone at the upstream end of the reach. The lower reaches at all sites have very similar valley floor width indexes. The same is true for the valley floor width values in the constricted reaches.

Contrasts in the valley floor width between the upstream and downstream reaches can be explained by several mechanisms. One may be that changes in geologic type and structure pre-determine the valley floor width (McHugh, 1986). There is no evidence in outcrops that there is this reach to reach change in the geology at each of the study sites.

A second hypothesis is that the earthflow constriction is a long term feature (10^3 - 10^4 yrs.) and during a wetter climatic period movement rates were more rapid, and the amount of sediment moving through the system was greater. During such a period, periodic, large earthflow movements would block the channel, forming a short-lived lake upstream of the constricted reach, causing deposition as the lake formed, and wide scale channel reworking as the blockage failed and the lake drained. This hypothesis would account for the extensive low surfaces that occur in the upper reaches. However, there is no evidence to support this hypothesis. and landslide-dammed lakes are rare in the western Cascades (Swanson et. al, 1985). Landslide-dammed lakes are more common in the Coast Range (Swanson et. al., 1985) where large-scale, catastrophic landslide movement is more common due to geologic factors.

A third hypothesis to account for the differences in channel width is that the upstream reach is an area of decreased slope due to aggradation in the earthflow reach resulting from deposition of large immobile particles. As the slope in the upper reach decreases, and the earthflow continues to constrict the valley floor, sediment deposition will occur in this upper reach due to a hydraulic backwater effect (Kieffer, 1985). This fluvial deposition may cause for lateral changes in channel position within the valley floor. Along with fluvial deposition of materials, other mechanisms of transport such as debris flows from upstream tributaries may also add particles which may be deposited in this upper reach. Evidence of debris flow deposition in the upstream reaches has been seen at FPC (1964 storm, Grant, 1986) and Jude Creek (Feb. 1986). Debris flow deposits change not only the channel pattern and morphology, but the valley floor morphology as well. This third hypothesis seems the most likely, especially in terms of presently occurring processes.

CHAPTER 4

CHANNEL GEOMETRY

Earthflow movement can effect the longitudinal profile of a channel (Kelsey, 1977), thereby changing channel hydraulics and configuration. Analysis of channel configuration is aided by recognizing that structures and processes occur over a range of hierarchical scales. Frissell et. al. (1986), Grant (1986), and Rosgen (1985) all classify the channel at several scales. Rosgen (1985) classifies sections of streams based on description of morphological and hydraulic variables. This classification is quite complex, including four stream types and multiple variations on each type, depending on channel gradient, sinuosity, valley confinement, soil stability, channel width to depth ratio, and dominant particle size. For each classification unit there are additional descriptors, including flow regime, depositional features, meander patterns, and riparian vegetation. This classification is descriptive of channel form and flow pattern, but it does not address the effects of valley floor and valley wall geometry and position within the drainage network on the structure and function of the channel.

On the other hand, Frissell et. al. (1986) uses a hierarchical approach to watershed classification. Their system covers several spatial scales: watershed, segment, reach, pool-riffle system, and microhabitat (Fig. 19). This classification system not only divides the watershed spatially but it also divides it temporally, since

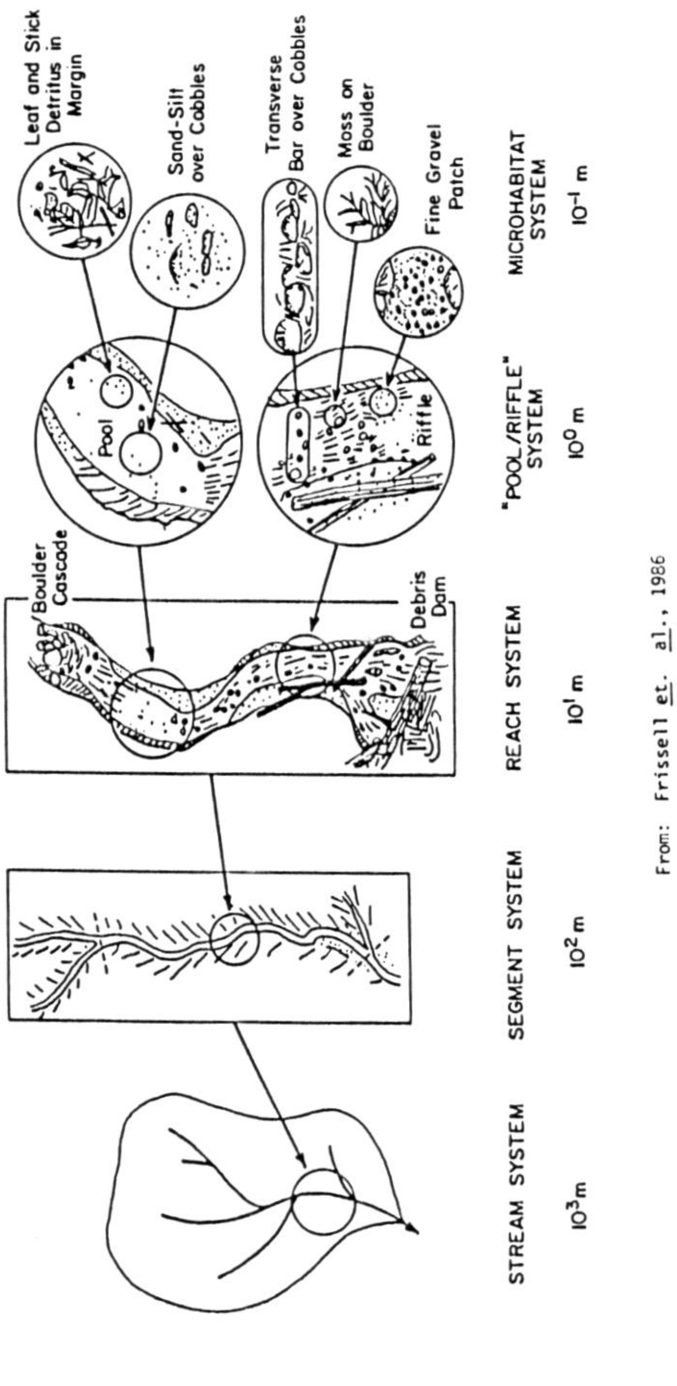

Figure 19 - Frissell et. al.'s (1986) stream network classification.

features at the different space scales have characteristic time scales of persistence. Microhabitats may change yearly while the larger segment may persist for thousands of years without major change. At the channel unit scale Frissell et. al. (1986) defines 5 pool and 5 riffle types as well as having a separate class for side channels. No size limits are specified for these channel units so, as in the channel unit description of Hayward (1980), there may be units within larger units.

Grant's (1986) channel classification focuses analysis on the channel unit scale and distinguishes five channel units: pools, rapids, cascades, and bedrock and log falls. These units are distinguished by their area of supercritical flow (visual percentage) and unit gradient. Channel units are at least one channel width in length with the exception of bedrock and log falls which cross the entire channel, but may be less than one channel width in the downstream direction. Sub-habitats were not treated as individual units so backwater pools, which were individual units in Frissell's pool-riffle system, are not included in this classification.

The classification scheme used in this study is hierarchical, using terminology similar to Frissell et. al.(1986) and Grant (1986). This study uses three reaches at each site: the earthflow-constricted reach, an upstream reach, and a downstream reach. Each reach is on the scale of 10^2 to 10^3 meters in length which is larger than the reaches of Frissell et. al. (1986). While the model of Frissell et. al. (1986) is useful for determining fisheries habitats, the larger scale hierarchical model used in this study is more useful for geomorphic study.

Four channel unit types were identified in these reaches: pools, riffles, rapids, and cascades (Table 12). The units are defined similarly to those of Grant (1986) in that each unit must be at least one low flow channel width in length (in this study low flow width is the width of the channel unit rather than an average low flow width for the entire reach or site). Cascades in this study include log falls, and bedrock steps. Classification was done visually in the field as the data for each unit was collected.

FIELD METHODS

Each stream channel was mapped using a metric tape, hand held clinometer, compass, and stadia rod. The low flow and active channel widths were measured at the downstream end of every channel unit. Active channel width is defined by the width of the unvegetated channel. Active channel width may be similar to bankfull width in lowland streams; however, due to the large particle size in the channels used in this study, bankfull terraces are not easily discernible if they are present. The length of each unit was measured along its center line. The water surface slope of each unit was determined by measuring the difference in elevation of the water edge at the two ends of the unit using a hand-held clinometer. Estimated error for the water surface slope measurements is $\pm$ 0.01. The error of length measurements can be up

UNIT TYPE	PERCENT GRADIENT	PERCENT AREA IN SUPERCRITICAL FLOW	OTHER INDICATORS
POOLS	0 - 1%	< 15%	
RIFFLES	1 - 2.5%	0 - 30%	
RAPIDS	2.5 - 4%	< 55%	LARGE BOULDERS BUT NOT IN DEFINED STEPS
CASCADES	> 4%	> 50%	STEPS ARE WELL DEFINED, COMPLETELY CROSS THE CHANNEL

Table 12 - Channel unit types and associated characteristics at low flow.

to ± 2.0 meters for the longer units. The error on the width measurements is estimated to be ± 0.5 meters.

Other information collected during the mapping of the channel units includes the number of boulders greater than 1.5 meters in diameter, exposed bedrock (in terms of percent of channel unit length), occurring on either side and on the bed of the channel, and where present the characteristics of mid-channel bars such as vegetation type and height above low flow.

CHANNEL GRADIENT

The effects of earthflow constriction on the longitudinal profile are discussed by Kelsey (1977) and Swanson *et*. *al*. (1985) who describe a relatively steep channel gradient through earthflow-constricted reaches and a lower gradient channel above the constraint. Beschta (1983) describes a similar decrease in slope and increase in sediment storage above a constriction. However, Swanson and Swanston (1977) note that effects of the Lookout Creek earthflow have not been enough to change the longitudinal profile to a convex shape, but may have changed it from the typical concave profile to the present straight profile. Kelsey (1977) attributes the increase in channel gradients in earthflow-constricted reaches to aggradation of the channel by large, immobile material input from the earthflow toe. This material is too large for fluvial transport, thereby armoring the channel bed. The finer material, however, is transported out of the system. In constricted reaches, areas of fine sediment deposition may be found only where back water areas are formed. The type of material entering a channel may also increase the gradient. Abundant large organic material accumulations in the channel in the vicinity of the earthflow toe may cause aggradation upstream and a steepening of the gradient over the debris, producing a stairstep profile.

The decrease in the reach gradient upstream of a constriction is primarily due to the increased base level in the constricted reach, and also to the backwater effects which occur due to the valley floor constriction. These changes act as controls causing sediment deposition in the upper reach. Beschta (1983) noted that during periods of increased sediment transport, aggradation may occur upstream of gorges or man made constrictions. Florsheim and Keller (1987) describe the steepening of the energy gradient through bedrock constricted areas with less steep gradients above, due to the formation of a hydraulic backwater. The decrease in energy gradient upstream of the constraint parallels the changes in channel gradient and results in lower unit stream power, promoting sediment deposition.

It is hypothesized that the gradient of the constricted reach will be greater than the gradients of adjacent reaches due to the emplacement of large amounts of coarse material. This increase in slope will be reflected in a higher number of steep units (i.e. rapids and cascades) and, possibly, greater mean gradient of these units. Where an upstream flat has been created by bedload deposition in response to backwater formation and aggradation in the earthflow-constricted reach, the upper reach will have lower reach gradients than the adjacent reaches. The lower gradient is manifest in greater numbers of low gradient units i.e. pools and riffles.

RESULTS

Reach Gradient

The gradients of a particular reach reflect the slopes and lengths of the individual channel units within that reach; therefore, different reach slopes may be due to different proportions of channel units or differences in unit slopes for specific unit types.

At RNA, LAN and LLC the reach slope is greatest in the earthflow-constricted reach. For LLC and RNA the reach gradients above and below the earthflow are quite similar; while in the case of LAN the upper reach gradient is not as steep as the gradient of the reach downstream of the earthflow (Figs. 20a-e; Table 13). For FPC the slope of the earthflow reach is the least steep of the three reaches, and the lower reach is the steepest (Table 13). At LOC the earthflow-constricted reach and the lower reach are similar in slope, while the the upper reach is much steeper than the other two.

Differences in reach gradient between the five sites can be attributed to the original slope of the three reaches, the size of material entering into the creek, the presence or absence of a confining valley wall on the opposite bank, the position of the reaches within the drainage basin, and the length of the earthflow reach.

The small variation between slopes of lower and upper reaches of RNA and LLC may be an indication of the amount of earthflow

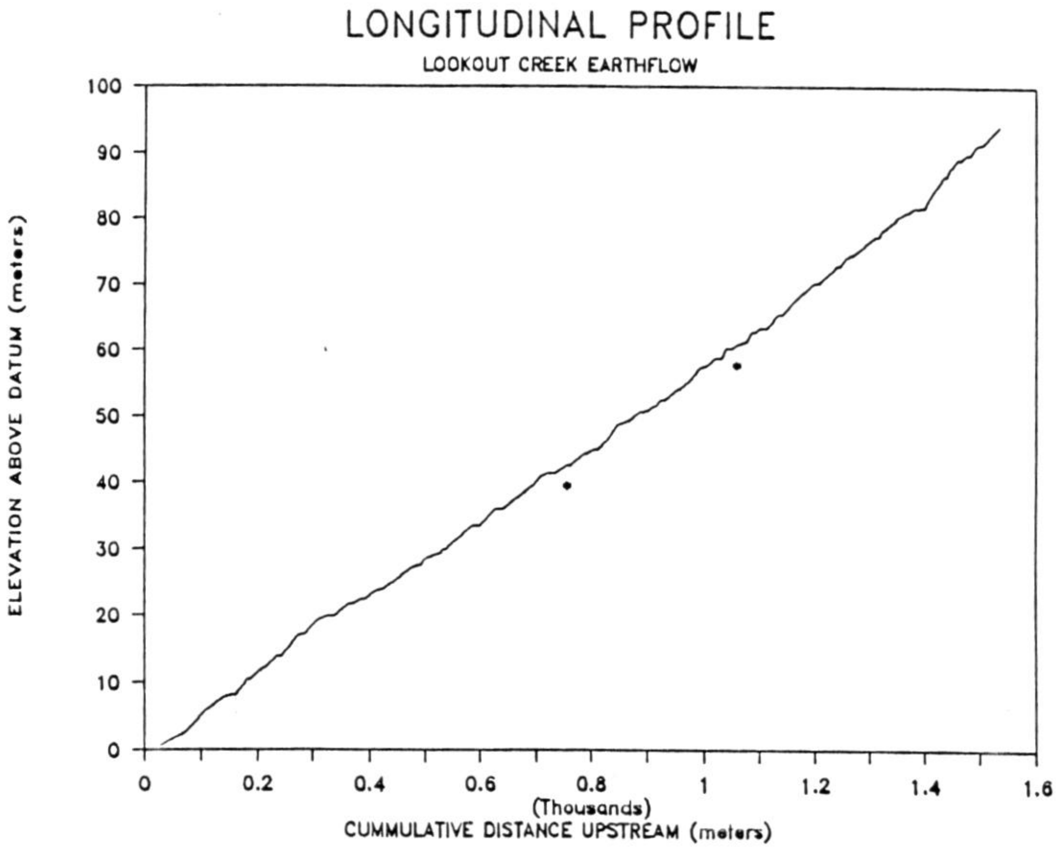

Figure 20a - Longitudinal profile of the Lookout Creek study site. * marks the boundaries of the earthflow reach.

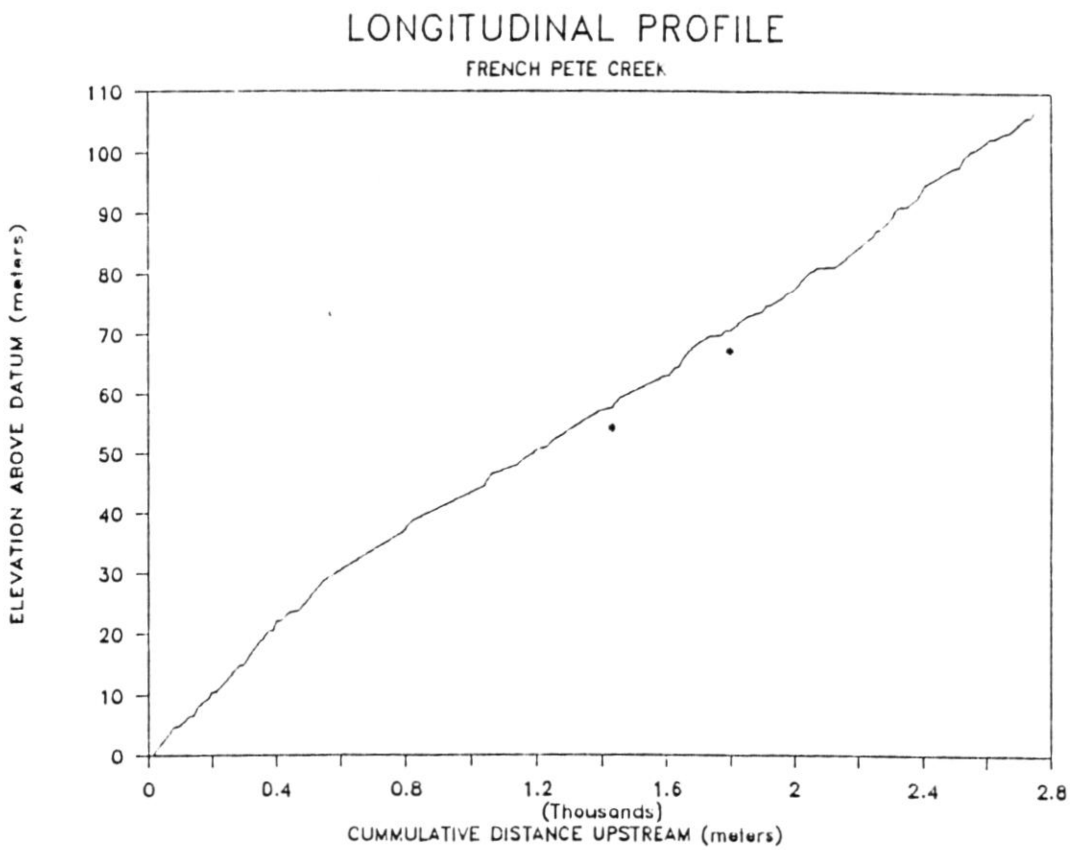

Figure 20b - Longitudinal profile of the French Pete Creek study site. * marks the boundaries of the earthflow reach.

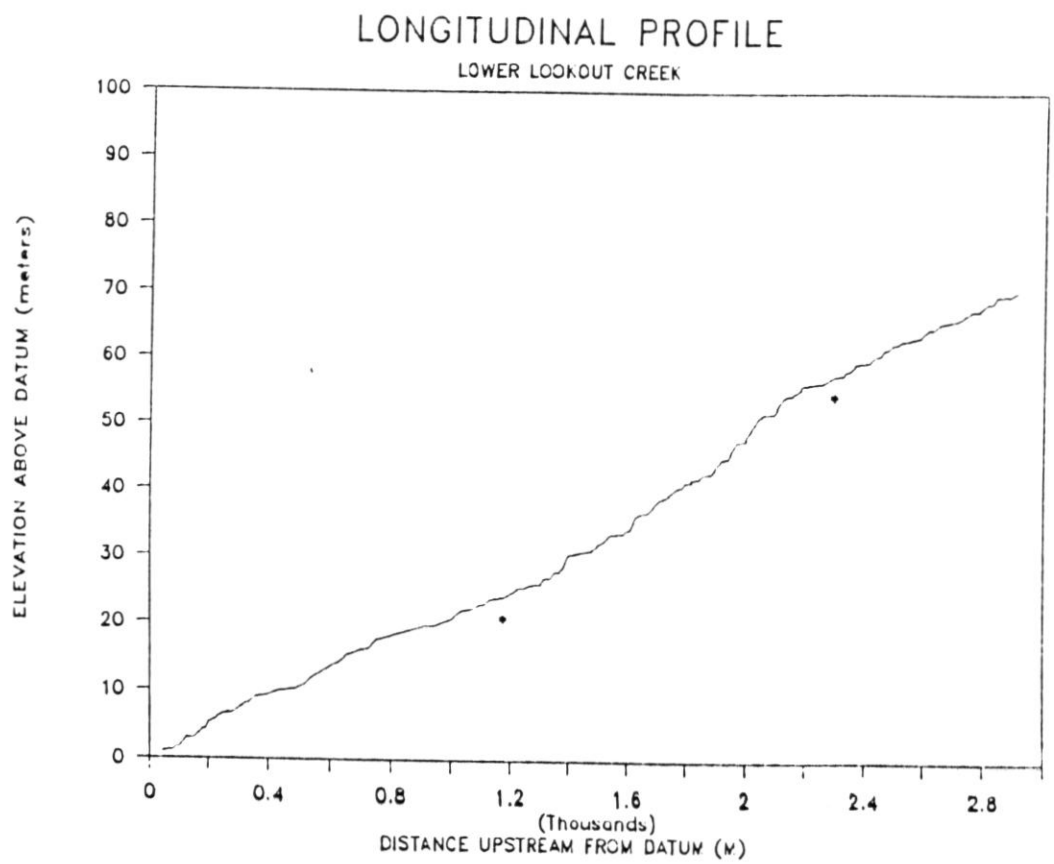

Figure 20c - Longitudinal profile of the Lower Lookout Creek study site. * marks the boundaries of the earthflow reach.

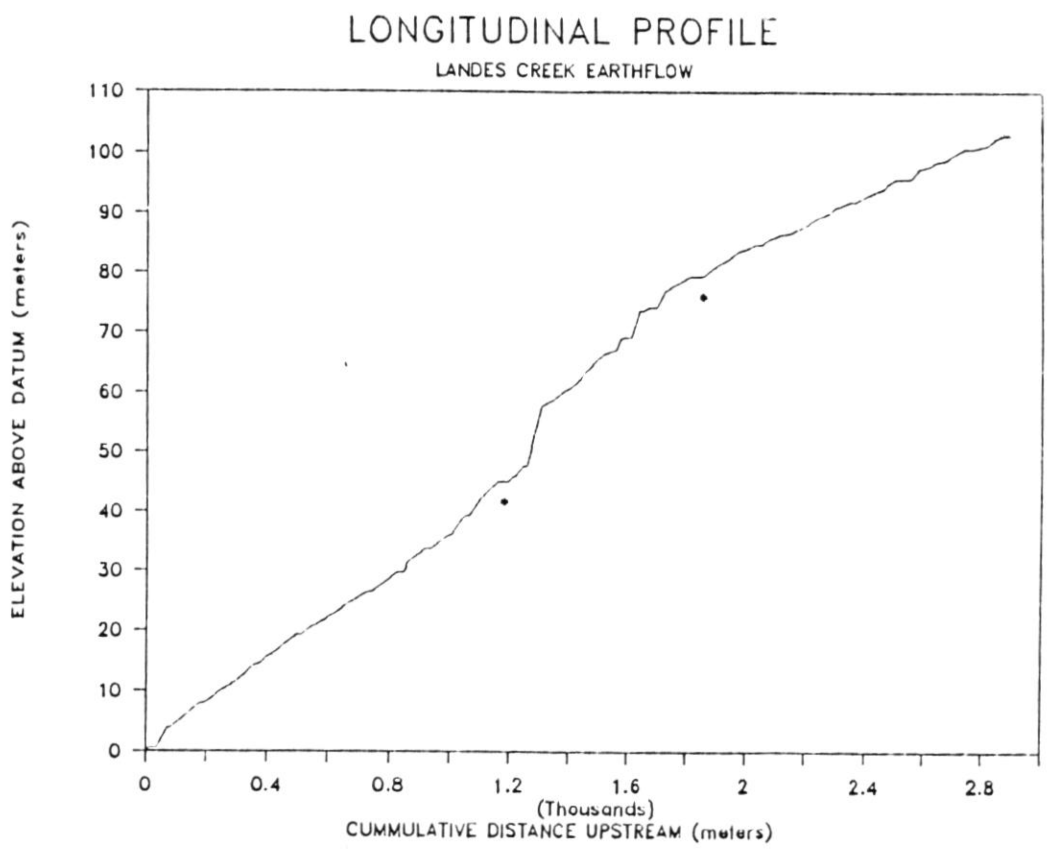

Figure 20d - Longitudinal profile of the Landes Creek earthflow study site. * marks the boundaries of the earthflow reach.

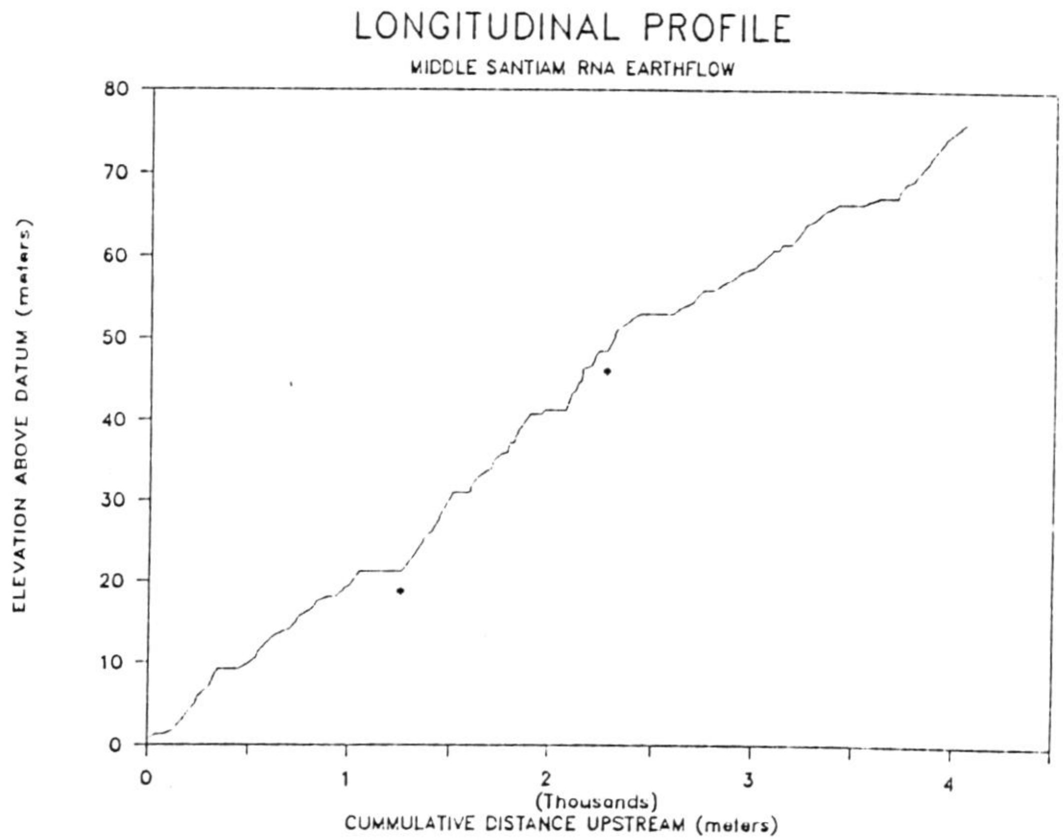

Figure 20e - Longitudinal profile of the Middle Santiam Research Natural Area earthflow study site. * marks the boundaries of the earthflow reach.

SITE	LOWER	REACH SLOPE (m./m.) CONSTRICTED	UPPER
LOOKOUT CREEK	0.056	0.060	0.071
FRENCH PETE CREEK	0.041	0.033	0.037
LOWER LOOKOUT CREEK	0.020	0.030	0.021
LANDES CREEK	0.041	0.052	0.023
RESEARCH NATURAL AREA	0.017	0.024	0.016

Table 13 - The gradient of each reach by site.

constriction or the overall influence of the slope steepening in the earthflow-constricted reach on the upstream reach. Earthflows which have not been constricting the channel for a long period of time, may not have a large effect on the channel gradient. The small variation in slope between the upper and lower reaches may also indicate that the increase in slope in the earthflow-constricted reach are local increases and not increases over the entire reach. Another hypothesis on the small variation in gradient may be that the transitions from the constricted reaches to the valley flats, combined with the small percentage of the flat being in the upper reach, may cause the lower gradient of the valley flat to be obscured. At RNA the transition into the valley flat as well as a transition into a bedrock constrained reach at the upstream end of the upper reach, may also obscure the lower gradient of the flat (Figs. 20d and 20e).

For LOC the pre-existing reach slope may be the main determinant of the present day slopes. Swanson and Swanston (1977) suggested that the straight long profile of LOC may be due to the earthflow aggrading the earthflow-constricted reach. This aggradation may not yet be great enough to form a convex long profile, but may have modified a concave profile. Also the high gradient in the upper reach may not permit deposition and formation of a flat.

FPC is similar to LOC in that there is not a steeper gradient in the constricted reach, but at FPC the steep lower reach may control the gradient of the constricted and upper reaches. The lower reach is the steepest and contains many boulders of possible glacial origin that armor the channel bed, thereby not allowing a change in base level. This is also combined with the very few large boulders found in the earthflow-constricted reach, which may indicate that this earthflow delivers fine material which is quickly moved out downstream, preventing aggradation of the channel bed.

The two sites which do not have a higher gradient in the earthflow-constricted reach (LOC and FPC) do not agree with the general model in which aggradation of large particles in the constricted reach increase the reach slope. This may be due to the overall gradient of the channel, the size of material entering the channel from the earthflow, and the the rate of material input into the channel from the earthflow.

Unit Configuration

The differences in slope among the three reaches at a site can be examined in terms of the differences in the relative proportion of individual channel units. Differences in proportions of units are expressed as the percentage of reach length and unit number in each unit type (Table 14).

The earthflow-constricted reaches of LAN, LLC, and RNA have the greatest percentage of cascades in terms of unit number and length compared to the other two reaches at each site. The upper reaches at these sites contain the highest percentage of riffles in terms of length and number. The extent of cascades in the upper reach is the lowest of the three reaches at these sites. Pools make up a greater percentage of channel length in the constricted reach than in the lower reach.

SITE	PERCENT OF TOTAL UNITS POOLS	RIFFLES	RAPIDS	CASCADES	PERCENT OF TOTAL REACH LENGTH POOLS	RIFFLES	RAPIDS	CASCADES	TOTAL NUMBER OF UNITS	TOTAL REACH LENGTH (meters)
LOOKOUT CR.-LOWER	28.3	19.6	17.4	34.8	14.2	23.4	22.2	40.2	46	761
LOOKOUT CR.-CONSTRICTED	40.0	8.0	24.0	28.0	27.8	12.7	31.9	32.7	25	313
LOOKOUT CR.-UPPER	33.3	11.1	25.0	31.6	17.9	11.5	34.8	35.8	36	459
FRENCH PETE-LOWER	32.3	3.2	16.1	48.4	10.7	1.2	47.1	40.9	31	1384
FRENCH PETE-CONSTRICTED	28.6	7.1	28.6	35.7	16.3	2.6	56.9	24.1	14	411
FRENCH PETE-UPPER	22.6	16.1	22.6	38.7	12.8	10.8	29.5	46.9	31	952
LOWER LOOKOUT CR.-LOWER	35.0	7.5	22.5	35.0	25.8	4.9	42.9	26.5	40	1179
LOWER LOOKOUT CR.-CONSTRICTED	31.3	14.6	14.6	39.6	27.3	21.6	18.3	32.8	48	1089
LOWER LOOKOUT CR.-UPPER	28.1	21.9	31.3	18.8	28.8	25.5	30.4	15.3	32	644
LANDES CR.-LOWER	31.0	10.3	37.9	20.7	16.1	6.0	62.6	15.4	29	1102
LANDES CR.-CONSTRICTED	26.1	13.0	26.1	34.8	20.2	12.1	39.7	28.1	23	660
LANDES CR.-UPPER	26.7	36.7	23.3	13.3	25.6	39.1	27.8	7.5	30	1025
RES.NAT.AREA-LOWER	22.6	25.8	32.3	19.4	27.3	31.6	32.5	8.5	31	1139
RES.NAT.AREA-CONSTRICTED	35.7	17.9	21.4	25.0	46.5	14.2	28.7	10.6	28	1130
RES.NAT.AREA-UPPER	20.0	36.7	33.3	10.0	26.8	35.7	34.8	2.7	30	1782

Table 14 - The percentage of each unit type in each reach by number and length of units.

The earthflow-constricted reaches at LOC and FPC are not steeper than the adjacent reaches; the lower reach at FPC and the upper reach at LOC are the steepest at each site. For these two sites the steeper reach is not the one with greatest percentage of length in cascades. The upper reach of FPC and the lower reach of LOC have greater percentages of unit length in cascades than the other two reaches at each site. The lower reach at LOC also has the highest percentage of number of units in cascades, but the lower reach at FPC has the greatest percentage of cascade units for this site. The earthflow-constricted reach in LOC contains the greatest percentage of pools both by number and length. The earthflow-constricted reach at FPC has the greatest percent length and percent number in rapids.

Within Unit Variability

There is variation in mean gradient among channel units of the same type among reaches. Therefore units in one reach may not be similar to units of the same type in another reach. This variability could cause reaches with the same distribution of channel units to have different reach gradients.

Generally the gradients of pools and of riffles are similar between reaches (Table 15; Figs. 21a-e). There are differences among the mean gradients of rapids among reaches at all sites except FPC; however, which reach has the steepest rapids varies between the sites (Table 15).

SITE	POOLS GRADIENT (%)	POOLS STD.ERR (%)	RIFFLES GRADIENT (%)	RIFFLES STD.ERR. (%)	RAPIDS GRADIENT (%)	RAPIDS STD.ERR. (%)	CASCADES GRADIENT (%)	CASCADES STD.ERR. (%)
LOOKOUT CR.-LOWER	0.27	0.12	3.78	0.49	5.13	0.58	9.27	0.69
LOOKOUT CR.-CONSTRICTED	0.30	0.15	3.00	0.00	7.58	0.74	11.50	2.31
LOOKOUT CR.-UPPER	0.08	0.08	4.38	0.94	7.33	0.62	12.33	1.63
FRENCH PETE-LOWER	0.52	0.15	-.-	-.-	3.11	0.38	7.15	0.81
FRENCH PETE-CONSTRICTED	0.64	0.09	-.-	-.-	3.28	0.80	7.50	1.17
FRENCH PETE-UPPER	0.82	0.32	3.11	2.31	3.27	0.70	5.97	0.65
LOWER LOOKOUT CR.-LOWER	0.21	0.07	0.27	0.80	1.83	0.22	5.00	0.74
LOWER LOOKOUT CR.-CONSTRICTED	0.37	0.09	0.93	0.20	2.71	0.26	10.52	2.35
LOWER LOOKOUT CR.-UPPER	0.51	0.12	0.86	0.18	3.54***	0.35	5.69	0.58
LANDES CR.-LOWER	0.22	0.15	2.00	0.00	4.09*	0.21	6.58	1.13
LANDES CR.-CONSTRICTED	0.17	0.17	2.00	0.29	3.25	0.40	10.07	2.01
LANDES CR.-UPPER	0.38	0.16	2.30	0.15	3.36	0.21	6.13	0.66
RES.NAT.AREA-LOWER	0.00	0.00	1.25	0.13	2.78	0.32	7.00	0.73
RES.NAT.AREA-CONSTRICTED	0.25	0.13	2.20*	0.25	3.58##	0.37	8.57*	1.02
RES.NAT.AREA-UPPER	0.00	0.00	1.16	0.17	2.78	0.30	5.33	0.33

* Unit is significantly greater (P>0.1) than same unit in different reaches.

*** Upper reach unit is significantly greater (P>0.1) than similiar unit in lower reach

\## Constricted reach unit is significantly greater (P>0.1) than similiar unit in lower reach.

Table 15 - The mean and standard error of gradient for each unit within each reach. Tukey's test was used to test significance.

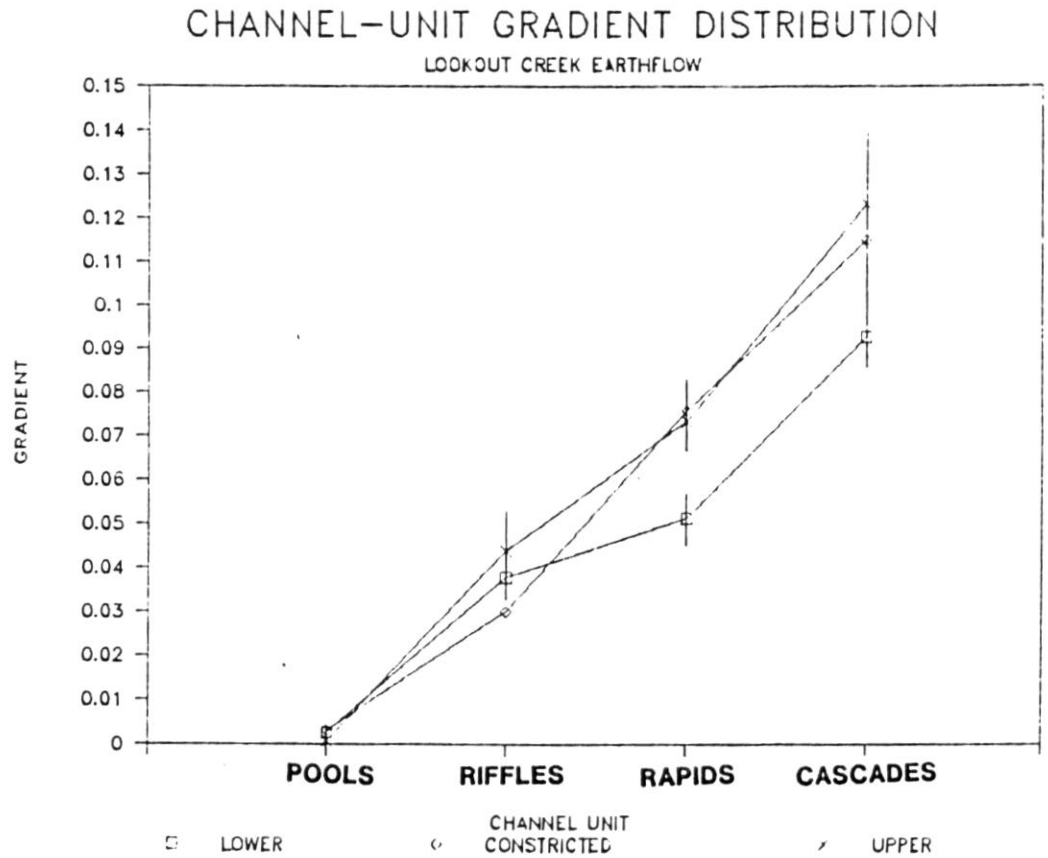

Figure 21a - The mean unit gradient distribution of each channel unit type for each reach at the Lookout Creek earthflow site.

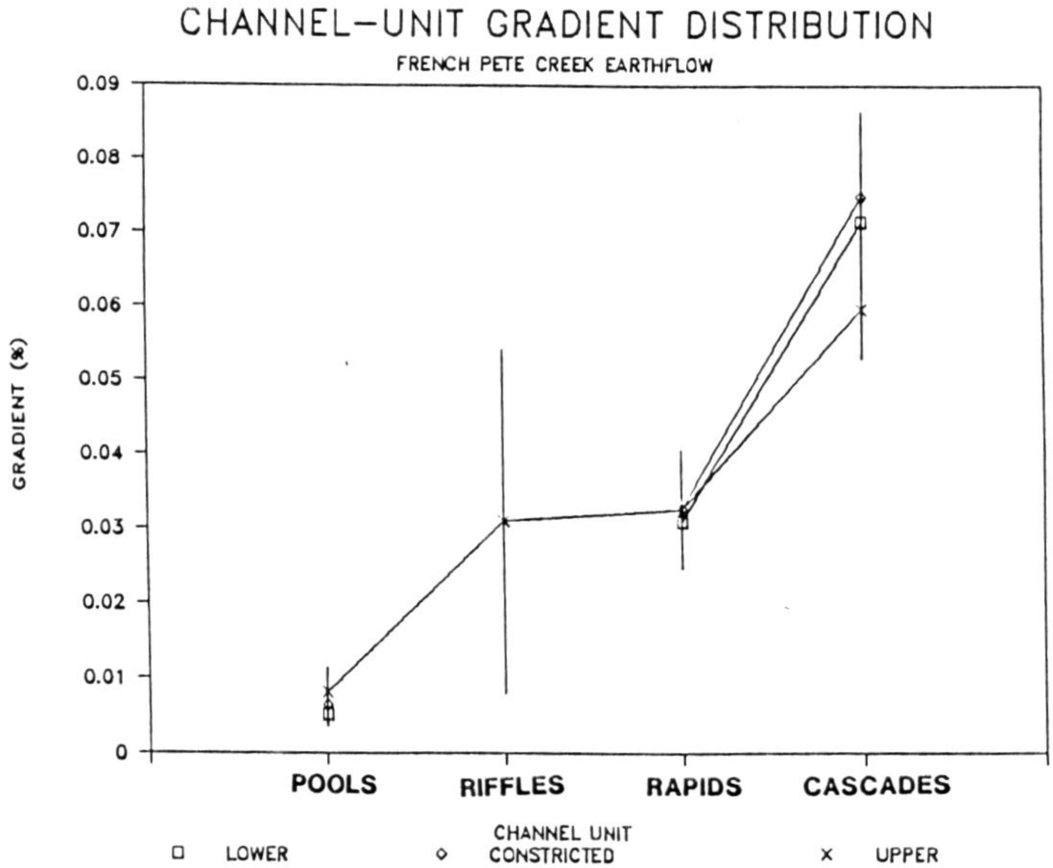

Figure 21b - The mean unit gradient distribution of each channel unit type for each reach at French Pete Creek.

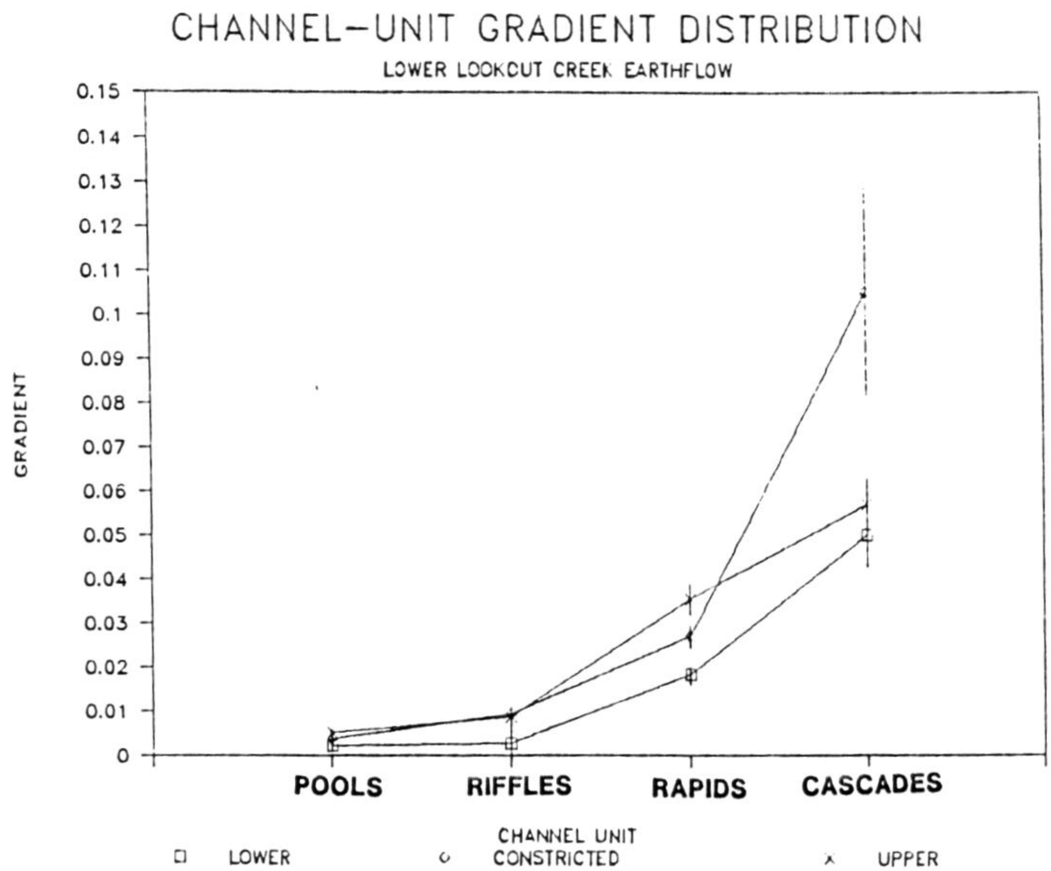

Figure 21c - The mean unit gradient distribution of each channel unit type for each reach at the Lower Lookout Creek earthflow site.

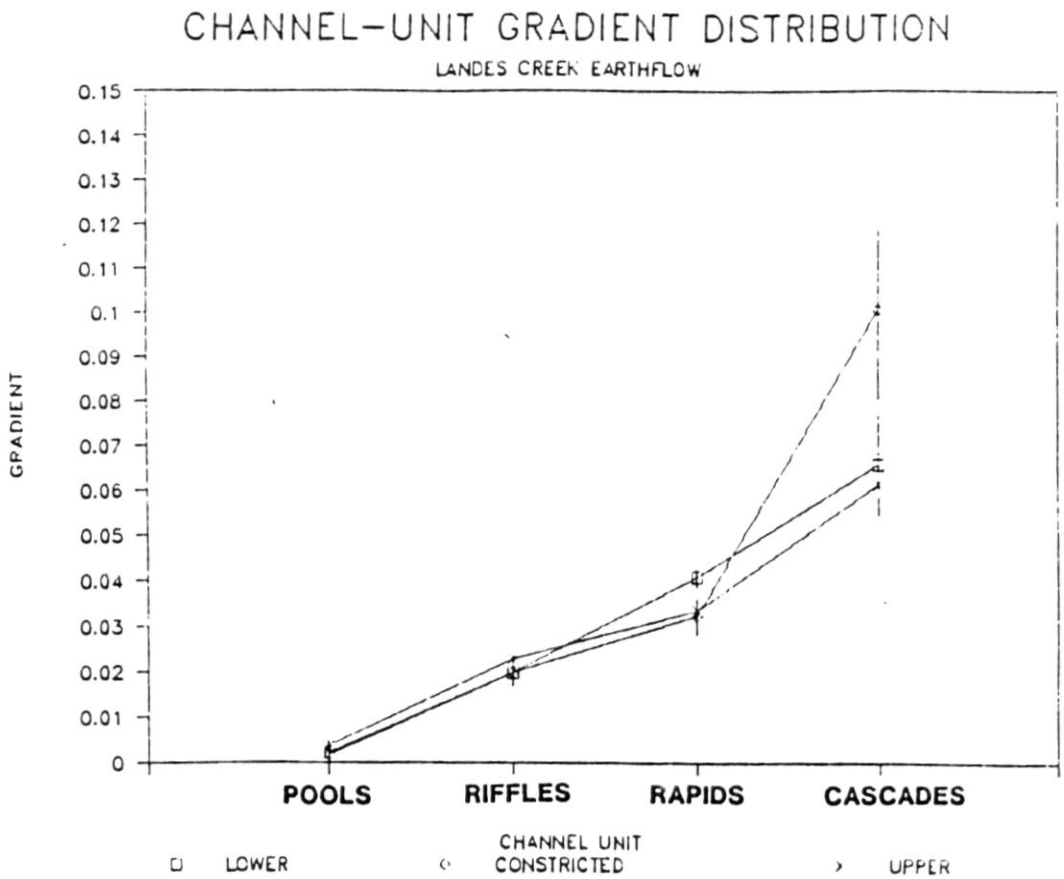

Figure 21d - The mean unit gradient distribution of each channel unit type for each reach at the Landes Creek earthflow site.

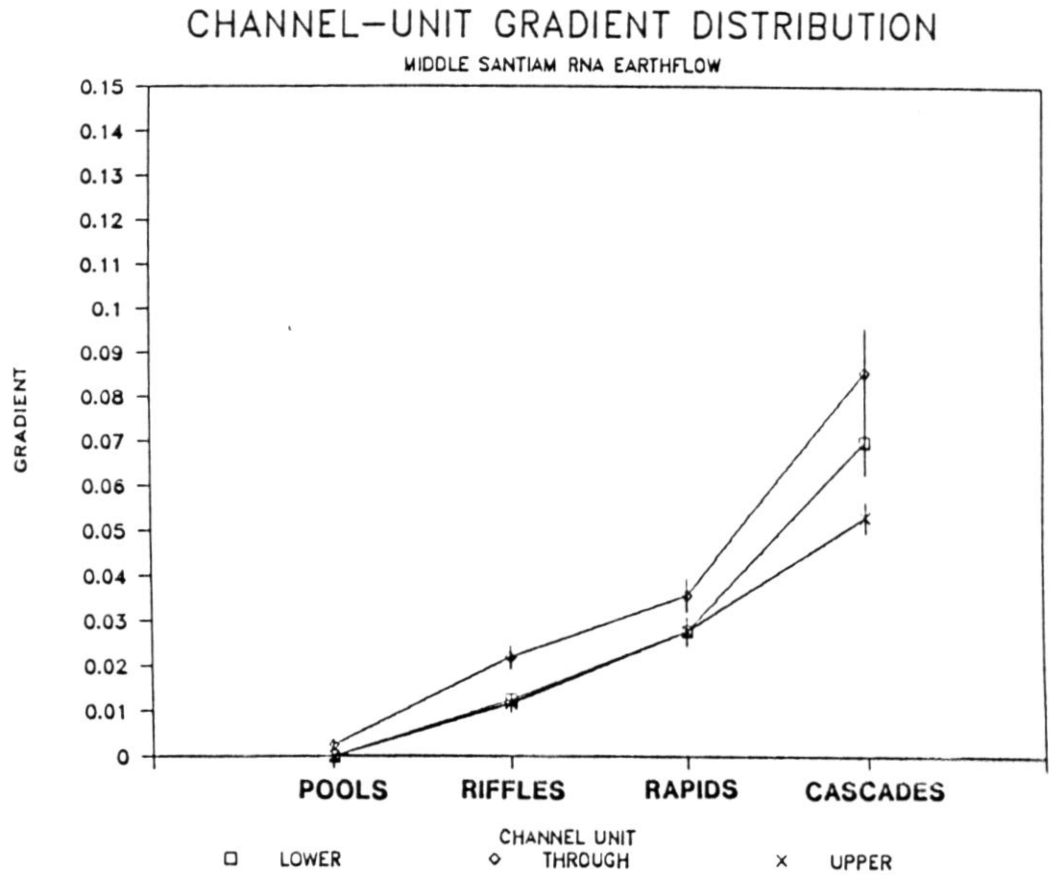

Figure 21e - The mean unit gradient distribution of each channel unit type for each reach at the Middle Santiam RNA earthflow site.

The cascade gradients are the must variable among reaches. For LLC, RNA, and LAN the mean gradient of the earthflow-constricted reach cascades are steeper than those in the upper reach. In all cases the steepest reaches have the cascades with the steepest gradients for a site. For the three sites where the earthflow-constricted reaches are the steepest, this is important since cascades are more prominent in this reach type than in the adjacent reaches. The steeper unit gradient and the greater number of cascades in these reaches account for the greater slope of the entire reach.

CHANNEL PLANIMETRIC VIEW

The planimetric form of the stream channel may be constricted within the earthflow-constricted reach if the rate of channel constriction exceeds the rate of material removal by the channel. The constricted reach may be narrower in the earthflow reach for two reasons: direct constriction by earthflow movement, or hydraulic channel-form response to the steeper gradient. The steeper gradient in the constricted reach observed at some of the sites would promote a greater velocity through this reach, favoring development of a narrower channel than the lower gradient upstream reach.

Another mechanism for changes in channel width is that earthflow movement may be great enough to constrict the channel. The magnitude of the effect of earthflow constriction on channel width is dependant on the balance between the rate of earthflow toe encroachment into the stream and the rate of removal of this material (Fig. 3). The physical earthflow constriction may be the only factor in changing channel morphology for the two sites where the steepest slope is not found in the constricted reach; it is also a factor for the other three sites where the change in reach gradient is also important.

It is hypothesized that without the influence of exogenous controls, channel units of the same type will have similar geometries (length to active width ratios) thereby allowing comparison of channel units between streams of different sizes. If this is true, areas with narrower channels will also have shorter channel units.

RESULTS

Reach Width

The average low flow channel width is not substantially different among the three reaches at each site (Table 16). However, the mean active channel widths of the upper reaches for LAN, LLC, and RNA are wider than the other two reaches at each of these sites, and channel widths do not vary between the lower and earthflow-constricted reaches. Although the upper reaches at these sites have lower slope than the earthflow-constricted reach, their stream reaches have gradients similar to those of the lower reaches. This implies that a principal effect of the constriction is widening of the active channel in the upstream reach, not constriction of the channel in the earthflow-constricted reach. The change in width is due in part to the lower gradient and the increased deposition in the upper reach. The constriction of the

SITE	MEAN LOW FLOW WIDTH (meters)	STANDARD ERROR (meters)	MEAN ACTIVE WIDTH (meters)	STANDARD ERROR (meters)
LOOKOUT - LOWER	6.7	0.4	9.4	0.3
LOOKOUT - CONSTRICTED	5.0	0.4	8.4	0.4
LOOKOUT - UPPER	5.3	0.4	7.5	0.5
FRENCH PETE - LOWER	11.2	0.9	20.3	1.0
FRENCH PETE - CONSTRICTED	9.5	0.8	20.2	1.5
FRENCH PETE - UPPER	9.2	0.5	18.8	1.2
LOWER LOOKOUT - LOWER	10.0	0.5	18.0	0.9
LOWER LOOKOUT - CONSTRICTED	9.6	0.6	19.5	1.0
LOWER LOOKOUT - UPPER	8.0	0.8	27.9	1.5
LANDES - LOWER	13.1	0.8	17.9	0.6
LANDES - CONSTRICTED	11.9	1.1	16.7	1.0
LANDES - UPPER	12.7	1.0	22.6	1.0
RES.NAT.AREA - LOWER	15.0	1.1	27.9	1.3
RES.NAT.AREA - CONSTRICTED	14.9	1.1	28.5	1.4
RES.NAT.AREA - UPPER	14.2	0.9	35.1	1.9

Table 16 - Mean low flow and active channel widths for each reach at each site.

valley floor in the earthflow-constricted reach acts as a hydraulic control, forming a backwater effect in the upstream reach and causing bedload deposition. Also involved in this deposition is the gradient transition from the steep earthflow-constricted reach to the lower gradient upper reach.

The similar mean active widths for the lower and earthflow-constricted reaches at the sites implies that the flow regime through the earthflow carries on downstream of the earthflow and does not cause channel expansion below the constriction as predicted using the model of Florsheim and Keller (1987). Or if the expansion occurs it is over the course of very few units, not the length of the reach.

For FPC there is no significant difference in the active channel widths between the three reaches. The mean active channel width of the earthflow-constricted and upper reaches at LOC are slightly narrower than the lower reach. The narrow average active channel width in the upper reach of LOC may be due to the channel pattern of this reach. This reach contains three well established (vegetated with old growth Douglas fir) 1.5 meter high central bars which divide the flow into narrower channels. However, because of lack of contrasts in reach gradients, a wider channel in the upper reach is not expected.

In all cases the channel bank opposite the earthflow toe, consists, in part, of bedrock, implying that the flow must be eroding the earthflow toe as it encroaches on the stream, in order to be maintaining the active channel width which is not narrower than the active width of the other reaches.

Unit Width

A wider mean channel at the reach scale is the result of greater mean channel widths on the channel unit scale. For the three sites where the upstream reach is the widest reach (LAN, LLC, and RNA) the average active unit widths are greater than the average widths of the other two reaches. However, the greater width is only significant ($p > 0.10$) for particular units at each site (Table 17). For LLC pools and rapids in the upper reach are significantly ($p > 0.10$) wider than the same units in the lower reach. For LAN rapids and cascades in the upper reach are wider than those in the lower and earthflow-constricted reaches respectively. For RNA pools in the upper reach have a greater width than those in the lower reach, but not the earthflow-constricted reach. For all other unit types at these three sites channel units in the upstream reach are widest, but the ability to examine statistical significance is limited by small sample sizes.

The mean active channel unit width for FPC and LOC vary between reaches in no consistent pattern. Generally the width of channel, at those two sites, units does not differ significantly among reaches (Table 17).

Unit Length by Reach

The effects of earthflow constriction on the average length of channel units was hypothesized to be similar to that of the channel width: where channel width is less, channel unit length would be

SITE	POOLS ACTIVE WIDTH (meters)	POOLS STD.ERR (meters)	RIFFLES ACTIVE WIDTH (meters)	RIFFLES STD.ERR. (meters)	RAPIDS ACTIVE WIDTH (meters)	RAPIDS STD.ERR. (meters)	CASCADES ACTIVE WIDTH (meters)	CASCADES STD.ERR. (meters)
LOOKOUT CR.-LOWER	8.79	0.47	10.42	0.95	9.54	0.43	9.13**	0.72
LOOKOUT CR.-CONSTRICTED	7.47	0.73	11.35	0.00	8.13	0.55	7.94	0.90
LOOKOUT CR.-UPPER	8.40	0.88	8.35	1.90	7.14	1.25	6.03	0.49
FRENCH PETE-LOWER	19.97	1.37	-.-	-.-	19.68	2.29	15.98	1.72
FRENCH PETE-CONSTRICTED	15.80	0.48	-.-	-.-	24.38	3.69	20.26	2.25
FRENCH PETE-UPPER	16.53	1.78	20.72	4.03	23.29	3.30	16.63	1.18
LOWER LOOKOUT CR.-LOWER	17.01	0.79	24.97	3.79	19.71	2.52	16.33	1.42
LOWER LOOKOUT CR.-CONSTRICTED	19.47	1.73	21.43	2.03	16.64	1.39	16.64	1.39
LOWER LOOKOUT CR.-UPPER	30.51***	3.03	26.97	3.07	29.51***	2.76	22.48	2.96
LANDES CR.-LOWER	17.99	1.17	19.37	2.09	17.30	0.94	17.12	1.70
LANDES CR.-CONSTRICTED	17.25	1.68	18.17	0.15	18.27	2.97	13.87	1.12
LANDES CR.-UPPER	21.79	1.17	23.15	1.56	23.16***	3.08	22.05***	3.19
RES.NAT.AREA-LOWER	28.31	1.88	28.56	2.79	28.58	2.60	24.27	3.72
RES.NAT.AREA-CONSTRICTED	30.10	1.70	28.70	3.07	26.73	1.98	27.09	4.41
RES.NAT.AREA-UPPER	35.54***	3.71	33.91	3.12	33.14	3.92	35.50	11.78

** Lower reach unit is significantly greater (P>0.1) than similiar unit in upper reach

*** Upper reach unit is significantly greater (P>0.1) than similiar unit in lower reach

*** Upper reach unit is significantly greater (P>0.1) than similiar unit in constricted reach.

Table 17 - Mean active channel widths for each channel unit type at each site. Tukey's test was used in statistical analysis.

less in order to maintain a constant length to width ratio. The number of channel units in each reach is variable, as is the size of each channel, and the length of each reach. Due to this variability, the average unit length of each reach could not be used in comparisons between sites. Instead, the number of channel units per 100 meters of channel length was used (Table 18). The three sites with the wider upstream reaches would be expected to have fewer channel units per 100 meters since the units would be longer. This is true only for RNA. For the other four sites the lower reach contains the longest units. Therefore other factors must affect the average channel unit length. Potential factors include the overall reach slope, individual unit slope, and presence of exogenous controls such as large boulders and bedrock.

It was hypothesized that the steeper reaches would have shorter units due to the stepped, longitudinal channel profile. The steepest reaches at LLC, RNA, and LAN are the earthflow-constricted reaches. Of these three sites, only LAN has the greatest number of units per 100 meters of channel length in the steepest reach. The upper reach at LLC and the lower reach at RNA have the longest channel units for those two sites. The earthflow-constricted reach at FPC, which is also the least steep reach, has the shortest channel units. LOC, which has a very similar active channel width in all three reaches has very similar unit lengths in the earthflow-constricted and upper reaches, even though the reach slopes differ.

SITE	REACH LENGTH (meters)	NUMBER OF EACH UNIT BY REACH				NUMBER OF EACH UNIT/100 m REACH LENGTH				
		POOLS	RIFFLES	RAPIDS	CASCADES	POOLS	RIFFLES	RAPIDS	CASCADE	ALL UNITS
LOOKOUT CR.-LOWER	761.4	13	9	8	16	1.71	1.18	1.05	2.10	6.04
LOOKOUT CR.-CONSTRICTED	313.4	10	2	6	7	3.19	0.64	1.91	2.23	7.98
LOOKOUT CR.-UPPER	458.7	12	4	9	11	2.62	0.87	1.96	2.40	7.85
FRENCH PETE-LOWER	1383.6	10	1	5	15	0.72	0.07	0.36	1.08	2.24
FRENCH PETE-CONSTRICTED	410.8	4	1	4	5	0.97	0.24	1.22	1.22	3.41
FRENCH PETE-UPPER	952.4	7	5	7	12	0.73	0.52	0.73	1.26	3.25
LOWER LOOKOUT CR.-LOWER	1178.5	14	3	9	14	1.19	0.25	.076	1.19	3.39
LOWER LOOKOUT CR.-CONSTRICTED	1089.0	15	7	7	19	1.38	0.64	0.64	1.74	4.41
LOWER LOOKOUT CR.-UPPER	643.8	9	7	10	6	1.40	1.09	1.55	0.93	4.97
LANDES CR.-LOWER	1101.7	9	3	11	6	0.82	0.27	1.00	0.54	2.63
LANDES CR.-CONSTRICTED	659.9	6	3	6	8	0.91	0.45	0.91	1.21	3.49
LANDES CR.-UPPER	1025.2	8	11	7	4	0.78	1.07	0.68	0.39	2.93
RES.NAT.AREA-LOWER	1133.8	7	8	10	6	0.62	0.71	0.88	0.53	2.73
RES.NAT.AREA-CONSTRICTED	1129.6	10	5	6	7	0.89	0.44	0.53	0.62	2.48
RES.NAT.AREA-UPPER	1782.3	6	11	10	3	0.34	0.62	0.56	0.17	1.68

Table 18 - Number of channel units per reach and the number of channel units per 100 meters of reach length.

Unit length for each reach was also examined using the ratio of mean unit length to mean active channel width. If channel units have similar form in plan view between sites, similar length to width ratios should occur. This is generally true (Table 19).

Unit Length

Although there are not differences in the ratios of mean length to mean active width at LOC, FPC, and RNA at the reach scale, there are differences in the ratios for the individual unit types between reaches. The length to width ratios for units vary among channel unit types, but generally are very similar between reaches (Table 20). This is especially evident at LOC.

The average unit length for each reach is generally not statistically ($p>0.1$) different than the other reaches at a site except for the upper reach at RNA, where the average unit length is greater than in the earthflow-constricted or lower reaches (Table 21). The average unit length of individual unit types within a reach is quite variable between reaches and between sites.

EXOGENEOUS INFLUENCES

The influence of exogenous features, such as bedrock outcrops, tree roots, log jams, and large boulders, on the formation and stabilization of channel features has been discussed by Lisle (1986, 1987), Grant (1986), Whittaker and Jaeggi (1982), and Keller and Melhorn (1978). Lisle (1986) discusses how stable bends and obstructions cause bar formation. However, work by Florsheim and Lisle (1985) and other work noted by Lisle (1987) indicate that

REACH	LENGTH (meters)	ACTIVE WIDTH (meters)	AVERAGE LENGTH/ACTIVE WIDTH (m/m)
LOOKOUT - LOWER	16.6	9.4	1.8
LOOKOUT - CONSTRICTED	11.6	8.4	1.4
LOOKOUT - UPPER	12.7	7.5	1.7
FRENCH PETE - LOWER	44.6	20.3	2.2
FRENCH PETE - CONSTRICTED	29.3	20.2	1.5
FRENCH PETE - UPPER	30.7	18.8	1.6
LOWER LOOKOUT - LOWER	29.5	18.0	1.6
LOWER LOOKOUT - CONSTRICTED	22.7	19.5	1.2
LOWER LOOKOUT - UPPER	20.1	27.9	0.7
LANDES CR. - LOWER	38.0	17.9	2.1
LANDES CR. - CONSTRICTED	28.7	16.7	1.7
LANDES CR. - UPPER	34.2	22.6	1.5
RES. NAT. AREA - LOWER	36.6	27.9	1.3
RES. NAT. AREA - CONSTRICTED	40.3	28.5	1.4
RES. NAT. AREA - UPPER	59.4	35.1	1.7

Table 19 - Length to active width ratios for each reach using the mean length and mean active width.

SITE	POOLS LENGTH/ WIDTH (m./m.)	STD.ERR (m./m.)	RIFFLES LENGTH/ WIDTH (m./m.)	STD.ERR. (m./m.)	RAPIDS LENGTH/ WIDTH (m./m.)	STD.ERR. (m./m.)	CASCADES LENGTH/ WIDTH (m./m.)	STD.ERR. (m./m.)
LOOKOUT CR.-LOWER	0.97	0.08	2.11	0.65	2.18	0.31	2.39	0.37
LOOKOUT CR.-CONSTRICTED	0.99	0.09	1.74	0.00	2.14	0.36	1.39	0.27
LOOKOUT CR.-UPPER	0.87	0.11	1.77	0.80	2.18	0.53	2.78	0.47
FRENCH PETE-LOWER	0.74	0.14	-.-	-.-	7.45	2.82	2.17	0.37
FRENCH PETE-CONSTRICTED	1.07	0.20	-.-	-.-	2.77	1.57	0.99	0.18
FRENCH PETE-UPPER	1.09	0.17	1.29	0.66	1.82	0.38	2.46	0.65
LOWER LOOKOUT CR.-LOWER	1.29	0.13	0.78	0.14	2.68	0.46	1.45	0.22
LOWER LOOKOUT CR.-CONSTRICTED	1.14	0.15	1.39	0.38	1.31	0.35	1.34	0.27
LOWER LOOKOUT CR.-UPPER	0.77	0.17	0.90	0.19	0.75	0.15	0.77	0.18
LANDES CR.-LOWER	1.07	0.11	1.16	0.15	3.48	0.83	1.78	0.02
LANDES CR.-CONSTRICTED	1.46	0.48	1.46	0.51	2.81	0.83	1.69	0.37
LANDES CR.-UPPER	1.49	0.31	1.61	0.16	1.82	0.40	0.91	0.15
RES.NAT.AREA-LOWER	1.51	0.22	1.60	0.24	1.39	0.23	1.04	0.52
RES.NAT.AREA-CONSTRICTED	1.82	0.46	1.28	0.41	1.97	0.56	0.72	0.15
RES.NAT.AREA-UPPER	2.40	0.46	1.76	0.35	2.35	0.77	0.50	0.16

Table 20 - The mean length to active width ratios of each channel unit type in each reach.

SITE	POOLS LENGTH (meters)	POOLS STD.ERR (meters)	RIFFLES LENGTH (meters)	RIFFLES STD.ERR. (meters)	RAPIDS LENGTH (meters)	RAPIDS STD.ERR. (meters)	CASCADES LENGTH (meters)	CASCADES STD.ERR. (meters)
LOOKOUT CR.-LOWER	8.32	0.59	19.81	5.03	21.09	3.41	19.14	2.45
LOOKOUT CR.-CONSTRICTED	7.13	0.79	19.85	0.00	16.67	2.43	11.77	3.00
LOOKOUT CR.-UPPER	6.68	0.85	13.15	5.79	17.71	2.41	16.57	3.38
FRENCH PETE-LOWER	14.86	2.42	-.-	-.-	130.4**	40.72	37.77	5.55
FRENCH PETE-CONSTRICTED	16.75	2.95	-.-	-.-	58.48	27.39	19.82	3.57
FRENCH PETE-UPPER	17.39	2.71	20.64	8.13	40.17	9.37	37.19	7.90
LOWER LOOKOUT CR.-LOWER	21.70	2.30	19.10	2.94	56.17**	15.28	22.28	2.89
LOWER LOOKOUT CR.-CONSTRICTED	19.81	2.09	33.64	11.67	28.47	5.00	18.79	3.35
LOWER LOOKOUT CR.-UPPER	20.62	3.42	23.46	4.79	19.58	2.24	16.37	3.59
LANDES CR.-LOWER	19.67	2.81	21.93	1.33	62.70	15.54	28.20	2.93
LANDES CR.-CONSTRICTED	22.20	5.50	26.57	9.33	43.62	10.43	22.89	4.98
LANDES CR.-UPPER	32.85***	7.60	36.40	3.33	40.74	9.65	19.20	3.06
RES.NAT.AREA-LOWER	44.27	8.69	44.81	7.48	36.86	5.37	16.13	3.79
RES.NAT.AREA-CONSTRICTED	52.54	11.71	32.08	7.31	54.07	14.65	17.06	2.69
RES.NAT.AREA-UPPER	79.68	10.37	57.87***	6.73	61.95	13.42	16.07	2.39

** Lower reach unit is significantly greater (P>0.1) than similiar unit in upper reach

*** Upper reach unit is significantly greater (P>0.1) than similiar unit in lower reach

*** Upper reach unit is significantly greater (P>0.1) than similiar unit in constricted reach.

Table 21 - The mean length of each unit type in each reach. Significance tested using Tukey's test.

transverse and diagonal bars may not form in channels with slopes greater than 0.02. In these systems bar features may be replaced by transverse ribs (Lisle, 1986, 1987). In high gradient systems rib features are important since they form stable bedforms under typical flow conditions (Whittaker and Jaeggi, 1982). Transverse ribs are usually constructed of coarse material which armors the channel bed.

Exogenous controls not only affect local channel morphology, they may also affect the overall valley floor morphology and channel slope. Large boulders emplaced into the creek by earthflow movement can aggrade the stream and cause increased slope (Kelsey, 1977). Channel slope is also affected by changes in the mean bed particle size (Hack, 1957; Wilcock, 1967). Hack (1957) also shows along stream changes in bedrock competence alter channel slope. However, Kelsey (1987) argues that lithologic controls in northern California such as those described by Hack (1957) for the Appalachians are not important in controlling channel slope: the boulder strewn reaches, formed by slow but chronic hillslope movement are more important, but only locally.

Bedrock is important on the local scale since it may affect channel morphology (Keller and Melhorn, 1978). Bedrock outcrops are responsible for impeding channel migration across the valley floor. Bedrock obstructions may also be responsible for fixing the locations of channel units such as pools (Lisle, 1987). Grant (1986) describes an association of bedrock outcrops and pools in French Pete Creek.

RESULTS

Large boulders and bedrock control channel flow pattern. For this study large boulders are defined as those with an intermediate axis greater than or equal to 1.5 m. The variability in numbers of boulders at each site, and in each reach is quite large (Table 22), as is the variation in reach length. Because of this variability, the density of large boulders in each reach (number of boulders per 100 sq.meters) was used to compare reaches (Table 22).

The lower and earthflow-constricted reaches have greater boulder densities than the upper reaches, except at LOC where boulder density in the upper reach is greater that in the earthflow-constricted reaches. However, except for RNA and LLC, all of the lower reaches have a greater boulder density than the earthflow-constricted reaches.

Boulder densities vary by unit within and between reaches. The lower and earthflow-constricted reaches have higher boulder densities than the upper reaches. The expectation that cascades units, which contain boulder steps, have the greatest percentage of boulders per unit is generally true (Table 23).

We might hypothesize that large boulders are emplaced in the earthflow-constricted and lower reaches by earthflow activity and downstream transport. The density of boulders in the upper reach may indicate the density of boulders that would be present in the lower and earthflow-constricted reaches if the earthflow were not present, unless deposition in the upper reach is great enough to bury the large boulders. Field observations indicate that the large boulders

SITE	NUMBER OF BOULDERS / REACH			BOULDERS / 100 $m.^2$ REACH AREA		
	LOWER	CONSTRICTED	UPPER	LOWER	CONSTRICTED	UPPER
LOOKOUT CREEK EARTHFLOW	388	51	122	5.35	1.86	3.40
FRENCH PETE CREEK EARTHFLOW	337	78	107	1.33	0.96	0.59
LOWER LOOKOUT CREEK EARTHFLOW	61	150	14	0.27	0.68	0.08
LANDES CREEK EARTHFLOW	877	479	7	3.99	4.39	0.03
RESEARCH NATURAL AREA EARTHFLOW	219	323	68	0.70	0.99	0.11

Table 22 - The number and density of large boulders in each reach. Boulder density is the number of large boulders per 100 m^2 of reach area.

REACH	POOLS	RIFFLES	RAPIDS	CASCADES
	PERCENT OF TOTAL BOULDERS BY UNIT FOR EACH REACH			
LOOKOUT - LOWER	10.57	18.56	21.39	49.48
LOOKOUT - CONSTRICTED	15.69	5.88	27.45	37.25
LOOKOUT - UPPER	16.39	4.92	28.69	50.00
FRENCH PETE - LOWER	10.09	1.78	31.16	56.97
FRENCH PETE - CONSTRICTED	5.13	1.28	61.54	32.05
FRENCH PETE - UPPER	12.15	12.15	12.15	63.55
LOWER LOOKOUT - LOWER	12.87	28.71	13.86	44.55
LOWER LOOKOUT - CONSTRICTED	25.00	0.00	3.57	71.43
LOWER LOOKOUT - UPPER	38.46	23.08	23.08	15.38
LANDES CR. - LOWER	9.58	7.64	64.08	18.70
LANDES CR. - CONSTRICTED	9.39	13.78	43.22	33.61
LANDES CR. - UPPER	0.00	71.43	28.57	0.00
RES. NAT. AREA - LOWER	5.94	37.44	39.27	17.35
RES. NAT. AREA - CONSTRICTED	37.15	15.48	21.05	26.32
RES. NAT. AREA - UPPER	26.47	24.91	36.76	7.35

Table 23 - The percentage of boulders per channel unit type for each reach at each site.

in the earthflow-constricted reaches were derived from the opposite bedrock bank as well as from the earthflow toe. Since boulder calving from bedrock walls occurs in the earthflow-constricted reach, similar mechanisms of boulder input may occur from within-reach sources in the other reaches. Other mechanisms for boulder input include bank erosion, reworking of fan deposits, and debris flow entry from tributary channels. Also, some of the boulders may be relict glacial deposits.

Bedrock is another exogenous factor that can affect channel unit formation and stabilization. At all sites the earthflow-constricted reach has the highest bedrock exposure, probably resulting from the earthflow pushing the channel against the opposite valley wall, thereby exposing rock in the bank and bed. The upper reaches of LAN, RNA, and LLC, the three sites which have greater active channel widths in the upper reach, have the lowest percentage of units with bedrock exposed (Table 24).

DISCUSSION

Variations between reaches and sites

Changes in channel gradient, on the reach scale, punctuate the area of earthflow impingement on the channel. At three of the five study sites (LAN, LLC, and RNA) the earthflow-constricted reach is the steepest reach at each site. Only at LAN is the upper reach the lowest gradient reach; at RNA and LLC the gradients of the upper and lower reaches are similar. These sites also have the highest density of large boulders in the earthflow-constricted reaches as

SITE	TOTAL NUMBER OF UNITS WITH BEDROCK INFLUENCE	NUMBER OF UNITS WITH BEDROCK PRESENT				PERCENT OF EACH UNIT WITH BEDROCK PRESENT				
		POOLS	RIFFLES	RAPIDS	CASCADES	POOLS	RIFFLES	RAPIDS	CASCADE	ALL UNITS
LOOKOUT CR.-LOWER	1	0	0	0	1	0.0	0.0	0.0	8.3	3.0
LOOKOUT CR.-CONSTRICTED	6	2	0	1	3	13.3	0.0	12.5	15.8	12.5
LOOKOUT CR.-UPPER	5	2	1	0	2	16.7	25.0	0.0	18.2	11.1
FRENCH PETE-LOWER	10	1	0	4	5	10.0	0.0	80.0	33.3	32.3
FRENCH PETE-CONSTRICTED	7	3	1	1	2	75.0	100.0	25.0	40.0	50.0
FRENCH PETE-UPPER	10	4	1	3	2	57.1	20.0	42.9	16.7	32.3
LOWER LOOKOUT CR.-LOWER	26	13	1	4	8	92.9	33.3	44.4	57.1	65.0
LOWER LOOKOUT CR.-CONSTRICTED	30	11	4	2	13	73.3	57.1	28.6	68.4	62.5
LOWER LOOKOUT CR.-UPPER	2	1	0	1	0	11.1	0.0	10.0	0.0	6.3
LANDES CR.-LOWER	14	6	0	4	4	66.7	0.0	36.4	66.7	33.8
LANDES CR.-CONSTRICTED	10	4	1	2	3	66.7	33.3	33.3	37.5	43.5
LANDES CR.-UPPER	3	2	1	0	0	25.0	9.1	0.0	0.0	10.0
RES.NAT.AREA-LOWER	12	5	3	1	3	71.4	37.5	10.0	50.0	38.7
RES.NAT.AREA-CONSTRICTED	16	7	2	2	5	70.0	40.0	33.3	71.4	57.1
RES.NAT.AREA-UPPER	9	4	3	1	1	66.7	27.3	10.0	33.3	30.0

Table 24 - The occurrence of bedrock in each reach and the percentage of each unit type in each reach with bedrock influence.

well as the highest percent of cascades per reach, and the cascades have gradients higher than in the adjacent reaches.

The steep slope, combined with the earthflow constriction of the valley floor, did not affect the average low flow or active channel widths of the earthflow-constricted reaches, which are very similar to those of the lower reaches. However, the average active channel widths of the upper reaches at RNA, LLC, and LAN are wider than those of the other two reaches at each site. The increase in active channel width in the upper reaches of these three sites is caused by an increase in deposition in this reach. The deposition is due to either the formation of a backwater (Appendix A) or the change in gradient between the upper and earthflow-constricted reaches due to aggradation in the earthflow-constricted reach, or a combination of these mechanisms. Similar changes in active channel width do not occur at LOC and FPC. The active channel widths of all three reaches at each site are similar. One reason may be that the earthflow-constricted reaches are not the steepest reaches. Also, the earthflow-constricted reaches do not have the highest densities of large boulders, nor do the cascades have the steepest gradients for cascade unit types, indicating that not all channels react similarly to earthflow constriction.

The major differences between the two sets of sites seem to be due to RNA, LAN, and LLC having their steepest reaches in the earthflow area, and LOC and FPC having their steepest reaches elsewhere. The steep slope in the constricted reaches is thought to result from an increase in slope due to accumulation of sediment including large boulders, which armors the channel and causes local slope increases. This is supported by the high density of large boulders in the constricted reaches. It is assumed that a large percentage of the large boulders in the constricted reaches are delivered to the channel by erosion from the earthflow toe or from the opposite bank. FPC and LOC do not have lower densities of large boulders in the constricted reaches than in other reaches at each site, implying that sediment entering the channel at LOC and FPC is not large enough to remain in place but is instead removed from the site. Therefore, channel gradient is affected by the size of material entering the channel due to earthflow activity. Another possible cause of the differences in gradient may be lithologic variability between reaches. However, there does not seem to be such large scale lithologic variability at the sites, and Kelsey (1987) states that steep boulder reaches are the main local control on slope and that slope is not controlled strictly by lithologic variation as described by Hack (1957).

Variations between units

The ratio of mean channel unit length to active channel width (Table 20) indicates that, in general, the channel units do not have similar geometries between reaches. The differences between sites may be due to the number of each unit type in each reach, variation in unit gradient between reaches, and whether the units are affected by exogenous factors such as bedrock and large boulders.

Each unit type has somewhat different characteristics among reaches. Unit lengths and unit gradients vary by unit and by reach. In the case of LOC the ratio of length to active channel width for each unit is similar between reaches; however, the ratios vary among units. In the case of LLC, the upper reach has ratios of length to active width which are generally lower than the those of the same unit in the other two reaches (Table 20).

Stable exogenous features can affect the shape of the channel units, and therefore cause variation in the ratio of length to active channel width of units within and between reaches. Lisle (1986), Hayward (1980), Keller and Melhorn (1978), Kelsey (1977), and Hack (1957) discuss the importance of exogenous controls on the formation and structure of channel bedforms. Large boulders can cause local increases in gradient in the form of steep channel units. For all of the sites, except LOC, the steepest reach contains the highest density of boulders. Cascades in these steep reaches contain highest percentage of boulders per reach compared to the percentage of boulders in cascades in the other reaches (Table 23). Cascades in the steepest reaches are also generally steeper than the cascades in the other reaches (Table 15).

Bedrock is associated with formation of pools (Lisle, 1986). The amount of bedrock affecting the channel varies among sites; however, greater percentages of units in the earthflow-constricted reaches contain bedrock than other reaches. Earthflow-constricted reaches do not have a higher percentage of pools associated with bedrock than other reaches, except for at FPC. In most reaches greater than 50% of the pools are associated with bedrock (Table 24). The reaches with less than 50% of the pools associated with bedrock are in areas of low overall bedrock exposure. Therefore, channel units are associated with exogenous materials and, in the case of large boulders, may be changed by their presence; however, this does not necessarily indicate that the units are formed in response to these features.

Variations in only one characteristic do not seem to be responsible for the differences in channel morphology between reaches. Exogenous factors, such as large boulders and bedrock, affect the gradient of the units and may affect the placement of units. Differences in the number of each unit type per reach also affect the reach morphology since, in general, unit types differ in gradient and ratios of length to width which can vary because of the exogenous factors.

CHAPTER 5

SUMMARY

1. Earthflow movement disrupts vegetation growing on the surface. Two stem form classes (straight with lean >5° (form-1) and curved base (form-3)) as well as the mean lean of the sampled stand provide logarithmic relationships with earthflow velocity. From these relationships the velocity of unmonitored earthflows can be estimated. A complicating factor, however, is that these relationships give different earthflow velocities for the unmonitored sites. The relationship for the 1B stems indicates recent movement, while the relationships between the Form 3 stems and the mean lean indicate the movement over the age of the stand.

2. Earthflow movement perpendicular to a major channel causes constriction of the valley floor, and may trigger development of increased valley floor width upstream of the constriction. In the case of slow moving landslides, such as earthflows, valley floor width constriction is a long term process, and is not quickly recovered after movement has ceased.

3. Constriction of the valley floor may or may not cause constriction of the active channel width. However, where valley floor constriction combines with a steeper slope in the constricted reach, the active channel upstream of the constriction is wider than that in other reaches at the site.

4. At sites where the constricted reaches are the steepest reaches, cascade channel units are most abundant. These cascades have a greater density of large (> 1.5 m) diameter boulders than the cascades in the adjacent reaches. These cascades are also the steepest cascades at each site.

5. In general, there is not a difference between reaches in terms of average channel unit length or low flow width at each site. However, at sites with the steepest slope in the earthflow-constricted reach, the active channel width of the upstream reach is significantly greater than the active channel width in the other reaches at the site. Apparently increased deposition of mobile bedload in this reach, due to backwater effects and a change in gradient, causes a change in channel morphology. The presence of secondary channels and multiple gravel bars in these upper reaches indicates that the upper reach channels are subject to frequent lateral changes in channel position.

6. Indirect evidence indicates that the steep slope in the earthflow-constricted reach is due to local increases in slope caused by input of coarse material from the earthflow toe and the opposite bank. Channel gradient change is a long term feature. The size of material entering the stream from the earthflow may be more important than the rate of material input over the long term, since after cessation of earthflow movement large immobile particles continue to affect channel morphology.

7. The model of the effects of earthflow constriction on channel and valley floor morphology included a steepening of the channel slope in the earthflow-constricted reach as well as the constriction of the channel width in this reach. The earthflow-constriction would then indirectly cause the formation of a low gradient valley flat upstream and a wider active channel in the upper reach due to bedload and debris flow deposition. Agreement with this model was found at LLC, LAN, and RNA except that channel constriction did not occur in the earthflow-constricted reach, implying that the present earthflow constriction rates are not great enough to constrict channel flow.

FPC and LOC did not follow the model. The earthflow-constricted reaches were not the steepest reaches at LOC and FPC. This is most likely due to the rate and size of material entering the channel in the earthflow-constricted reaches. The original slope of the area before constriction, and the time since earthflow-constriction began could be other factors which may affect why these two sites do not agree with the proposed model. The original slope may have been lower than it presently is, however, the earthflow has not been active enough to have caused a prominent change in the longitudinal profile as has occurred at the other sites.

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APPENDIX

APPENDIX A

BACKWATER EFFECTS

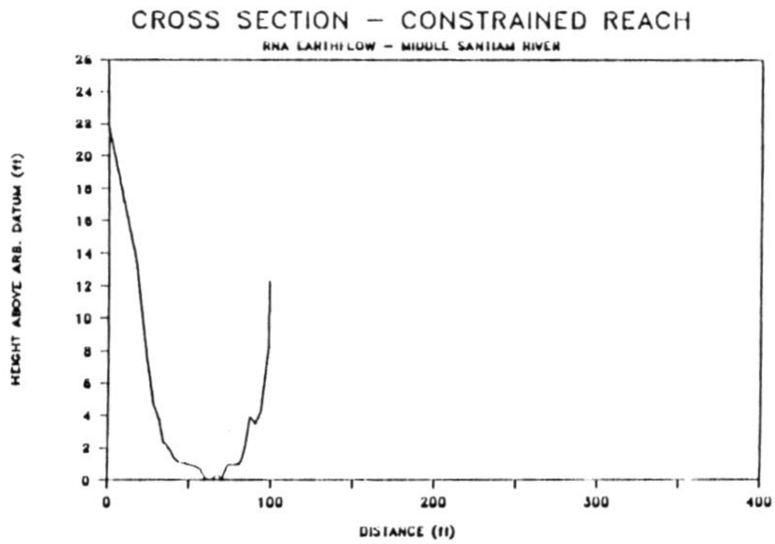
Backwaters form when the energy head upstream from a constriction is less than the energy needed for flow through the constriction. To determine if a backwater is presently forming at LAN and RNA, simple calculations were made using resistance equations to estimate a discharge, and specific energy equations to determine flow conditons under which backwaters form.

Hydraulic parameters of cross sections upstream of and within the constricted reaches of RNA and LAN (Figs. A1 and A2) were determined using a program of Grant (unpubl.). This program calculates cross sectional area at specific datums and corresponding velocities using resistance equations specifically developed for boulder-bed streams (Bathurst, 1978; Hey, 1979). Calculated parameters include area, average depth (d), width (w), wetted perimeter, relative roughness, and discharge (Q). At-a-station hydraulic geometry relationships were determined for the downstream cross sections so that common Q's could be used between the two cross sections.

Assuming a constant specific energy (E) between the two cross sections, E was determined for the upstream sites:

$$E = d + (q^2 / 2gd^2)$$

Where q is the specific discharge of the cross section (Q/w), and g is the gravitational constant. For a given E there is a defined maximum specific discharge (q_{max}).



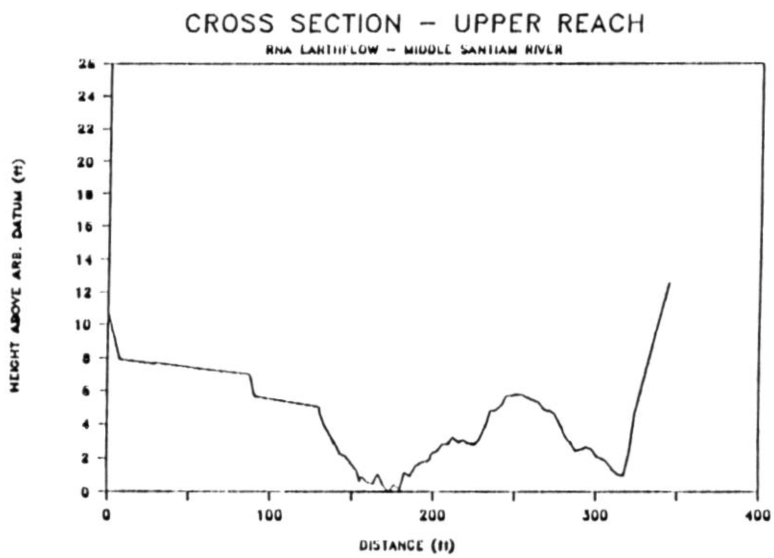
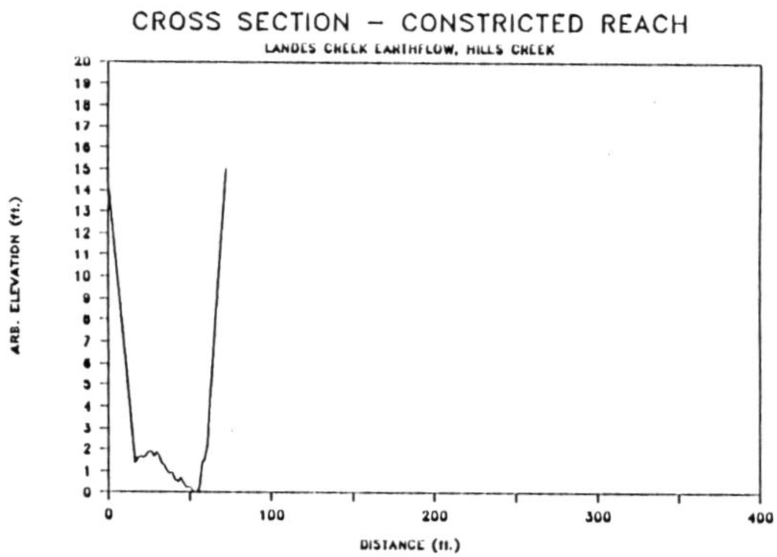


Figure A1 - Cross sections in constricted and upper reaches at the RNA earthflow site.



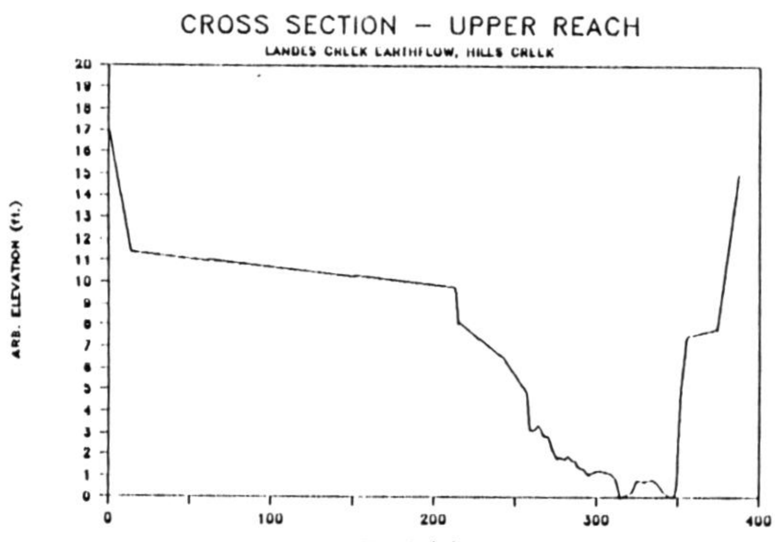


Figure A2 - Cross sections in the constricted and upper reaches at the Landes Creek earthflow site.

$$q_{max} = ((2/3\ E)^3 \times g)^{1/2}$$

Since we are assuming a constant E and Q for the two sites, q will change only with a change in width, thereby causing a change in d. If the specific discharge of the downstream cross section (q_b) is greater than q_{max} for the specific discharge (discharge is a constant) than the energy is not sufficent to allow flow through the constriction, causing a backwater to form upstream from the constriction (Kieffer, 1985). The backwater causes the specific energy (E) to increase to a new value (E_{back}), which is just large enough so that q_b will no longer exceede q_{max} (Kieffer, 1985).

$$E_{back} = 3/2\ (q_b^{\ 2}/g)^{1/3}.$$

Using these three equations, it was determined that backwaters do form upstream from the constriction (Tables A1 and A2). Recurrence interval of backwater occurence was determined by extrapolating flow-frequency data from stream gages downstream from the study sites (Friday and Miller, 1984). The extrapolation consisted of plotting a flow-frequency curve from known recurrence intervals at the gage, with the discharges multiplied by the percentage of the gaged basin the basin upstream from earthflow represents. This technique may cause the recurrence intervals of the flows to be lower or higher than they really are. The discharges at which backwaters form are less than the 1.5 yr. recurrence interval flow for both sites. Additional data must be collected in order to determine the distance upstream from the earthflow constriction, for the backwater to occur. However, it is thought that only flows which are transporting large amounts of sediment as bedload will change channel or valley floor characterisitics through deposition.

MIDDLE SANTIAM RESEARCH NATURAL AREA EARTHFLOW

RECURRENCE INTERVAL (yrs)	DISCHARGE (cfs)	q_a (ft^2/sec)	E (ft)	q_b (ft^2/sec)	q_{max} (ft^2/sec)	E_{back} (ft)	
	41.5	0.87	0.71	1.07	1.84	0.00	no
	109	1.64	0.98	2.45	2.98	0.00	backwater
	232	2.44	1.13	4.69	3.72	1.32	backwater
	374	2.98	1.30	7.07	4.58	1.74	
	683	5.01	1.74	11.86	7.10	2.45	
	1084	7.51	2.21	17.65	10.12	3.20	
1.02	1609	10.60	2.68	24.79	13.57	4.01	
1.04	2154	12.81	2.99	31.85	15.95	4.74	
1.07	2489	11.58	2.83	36.07	14.67	5.15	
1.17	3293	13.84	3.13	45.89	17.13	6.05	
1.45	4479	18.65	3.73	59.78	22.26	7.21	
2.1	5819	24.00	4.34	74.88	27.89	8.38	
2.6	6500	22.38	4.15	82.35	26.14	8.93	
4.3	7719	23.73	4.29	95.47	27.46	9.85	
8.7	9704	29.60	4.91	116.24	33.58	11.24	
9.0	11884	35.98	5.53	138.37	40.16	12.62	
23	14253	42.83	6.16	161.78	47.16	14.01	
> 25	16807	50.13	6.79	186.42	54.57	15.39	
> 25	19539	57.84	7.42	212.20	62.37	16.78	
> 25	22461	66.06	8.06	239.22	70.64	18.18	

q_a = the specific discharge for the upstream cross section

q_b = the specific discharge for the downstream cross section

E = specfic energy

E_{back} = specific energy of backwater

Table A1 - Hydraulic parameters needed to determine if backwaters form at the RNA earthflow site.