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Sediment Production and Delivery in Pistol River, Oregon
and its Effect on Pool Morphology

by

Periann Russell

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed April 18, 1994

Commencement June 1995



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AN ABSTRACT OF THE THESIS OF

Periann P. Russell for the degree of Master of Science in Geography presented on April 18, 1994.

Title: Sediment Production and Delivery in Pistol River, Oregon and its Effect on Pool Morphology

Abstract Approved: _____
Gordon Grant

Sediment production and delivery in Pacific Northwest coastal streams can have damaging effects on channel morphology and anadromous fish habitat. The research in Pistol River was designed to determine if a link exists between sediment delivery processes and degradation of fish habitat. Objectives of this basin-wide analysis were to: 1) identify and inventory major sources of sediment; 2) estimate rates, timing and volumes of sediment production and delivery to streams; and 3) attempt to link sediment delivery to changes in pool volumes. Two sets of data were collected and analyzed. The first set used aerial photos and field data to identify and estimate sediment production and delivery. The second data set used channel and pool measurements to estimate V^* , the percent of fine sediment in pools (Lisle and Hilton 1992).

Primary factors influencing landslides are unstable geology, steep slopes in inner gorges and management activity. Sediment production from landsliding increased as management increased while forested areas decreased. Sediment was delivered to Pistol River streams at a rate of $400\text{m}^3/\text{km}^2\cdot\text{yr}$.

Fine sediment in pools was primarily stored on edges and downstream ends of pools where shear stress is typically less than at pool heads and along the thalweg. A positive correlation was found between total fine sediment volume and scoured pool volume; however no relationship was found between V^* and scoured pool volume. This suggests that even though larger pools have the capacity to store more sediment, the percent of fine sediment occupying scoured pool volume is independent of pool size. The relationship between V^* and unit area sediment delivery was positive and strongly correlated but only after the effects of local sediment input were considered. A spatial and temporal relationship was found between V^* and time and distance of delivered sediment.

The relationship between fine sediment volume in pools and sediment delivery indicated that landslide sediment delivery from years past is being transported through the stream system and stored in downstream pools, bars and terraces. Narrow, upstream reaches temporarily trap recently delivered fine sediments.

Overall, in the short term (years), fine sediments are stored in pools in upland reaches. Over longer time scales (decades), sediment is transported downstream to unconstrained reaches where it is stored in various storage locations, including pools.

APPROVED:

Professor of GeoSciences (geography), in charge of major

Head of department of GeoSciences

Dean of Graduate School

Date thesis is presented April 18, 1994

Typed by Periann Russell

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The help, guidance and encouragement I have received while doing this project is beyond words. Because those that have supported me in this venture (or adventure) have contributed equally, I have chosen to list them rather than explain their individual contributions. The listed order is of no importance, I deeply appreciate all I have received.

In direct appreciation, there are exceptions. I must personally thank Gordon Grant for introducing me to, and recommending me for this project, and for believing that I could succeed. I must thank Cindy Ricks for her constant support, information and friendship. I am also in deep appreciation of my husband, Matthew Rubino, who I met while completing my field work in Pistol River when he was hired to help me finish that last season of pool measurements.

Ok, now the list.

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Sediment Production and Delivery in Pistol River, Oregon
and its Effect on Pool Morphology

INTRODUCTION

Sediment production and delivery in Pacific Northwest coastal streams can have damaging effects on channel morphology and anadromous fish habitat. Many studies have indicated fish population changes and declines caused by land use activity (Heifetz et al., 1986; Hicks et al., 1991; Scrivener et al., 1984; Reeves et al., in press) and subsequent increases in sediment delivery to streams. Much of this research has been conducted at the scale of stream reaches or tributaries and relates characteristics of spawning and hatching populations to land use. Other studies (Swanson et al., 1982; Dietrich et al., 1982.; Lehre 1982; Kelsey, 1982) have quantified sediment production, delivery, storage and transport by use of basin wide sediment budgets, but rarely has sediment data been correlated directly to a measure of fish habitat. Reeves (in press) stresses the need and importance of fish habitat research designed on a basin wide scale in order to fully understand the effects of land use on fish habitat diversity. Due to the complexity of sediment transport and routing, few studies have produced basin sediment budgets with the specific purpose of linking sediment delivery to fish habitat.

Pistol River, Oregon is one of many basins receiving increased attention from local communities and management due to declines in salmonid populations. According to Nehlsen et al. (1991), fall chinook salmon in Pistol River are at a moderate risk of extinction while coho salmon are at a high risk of extinction. Extinction categories were determined based on trends in anadromous fish populations and their habitat. Populations whose spawning escapements are declining were considered at high risk of extinction. The moderate risk category includes populations whose spawning escapements appear to be stable after previously declining more than expected from natural variation. Nehlsen et al. (1991) demonstrate similar population declines for anadromous species in other areas along the Oregon Coast, stating that most declines can be attributed to habitat damage resulting from land use development and forestry activities as well as overfishing or poaching. Pistol River is specifically mentioned as showing population declines of fall chinook primarily due to such logging impacts as accelerated sediment delivery to streams.

The possible relationship between sediment delivery to streams and fish habitat degradation in Pistol River has generated much controversy in the community. Residents, fishermen and Forest Service personnel have

anecdotally observed increased sediment in Pistol River for the past several decades. However, there are no systematic scientific studies to support their observations.

The research in Pistol River was designed to determine if a link exists between sediment delivery processes, including both natural and management accelerated processes, and degradation of anadromous fish habitat. The objectives of this basin-wide analysis were to: 1) identify and inventory the major sources of sediment in the Pistol River Basin; 2) estimate rates, timing and volumes of sediment production and delivery to streams resulting from primary sediment sources; and 3) attempt to link sediment delivery to changes in pool volumes. The amount of sediment produced on hillslopes was distinguished from the fractional percent that was delivered to the channel. This approach was used to emphasize the spatial aspects of hillslope processes contributing to fish habitat. For example, sediment production from road related landslides occurring on mid-slopes that is not delivered to a channel has different implications for fish habitat than sediment produced from inner-gorge landslides that is directly delivered to the channel.

The study concentrated on pool volumes since pools are critical habitat to anadromous fish for rearing and resting during their upstream and downstream migration (Everest et al, 1987). Pools also tend to act as sinks for fine sediments during waning flood flows and have been shown to be sensitive to sediment supply increases in other basins (Everest 1987; Lisle 1982, Lisle and Hilton 1992).

To meet the objectives of this study, two sets of data were collected and analyzed. The first dataset used aerial photographs and field data to identify dominant sediment sources and estimate sediment production and delivery to streams in the Pistol River basin. These data were analyzed with respect to geology and slope, land use, land ownership and time in order to define cause and effect relationships. The second dataset collected was the channel response data. Pool measurements were taken to estimate V^* , the percent of fine sediment filling pools (Lisle and Hilton 1992). Sediment delivery and V^* estimates were then analyzed together to determine the relationship between the amount of sediment delivered to the channel and the amount of fine sediment found in pools. The implications of these findings for channel geomorphology and fish habitat in Pistol River are considered.

THEORETICAL BACKGROUND

A sediment budget is defined as a quantitative description of sediment production rates, transport, storage and output by different processes (Dietrich et al. 1982; Swanson et al. 1982). In steep, mountainous landscapes in the Pacific Northwest, sediment production by mass wasting has been found to dominate erosion processes (Kelsey et al 1981; Kelsey 1982; Lehre 1982; Swanson and Grant 1982), though some studies have emphasized the importance of surface erosion as well (Dietrich et al. 1982; Ried 1991).

Sediment budgets provide important information concerning the amount of sediment within a system. However, routing of sediment through drainage systems is necessary to determine downstream effects. Sediment routing through streams is complex due to spatial and temporal variations of sediment production from hillslopes and streambanks, and poorly understood dynamics of sediment transport and storage. Recent research conducted by Lisle and Hilton (1992) in the Trinity River Basin presented a new method for assessing downstream effects of sediment supply by measuring the fraction of the residual volume of pools filled with fine sediment. They used the equation:

$$V^* = \frac{\text{Volume of Fine Sediment}}{\text{Volume of Fine Sediment} + \text{Volume of Water}}$$

where V^* is a dimensionless ratio which may serve as an index of excess sediment over transport capacity in natural gravel-bedded streams (Lisle and Hilton, 1992). The method was developed based on flume experiments suggesting that bed-surface material becomes coarser as sediment supply decreases (Dietrich et al. 1989). An increase in sediment supply can, therefore result in finer bed-surface material more readily transported during waning flows (Dietrich et al. 1989). Under these conditions, fine sediment is selectively transported from zones of high boundary shear stress, such as riffles, and deposited in zones of low shear stress, such as pools (Lisle and Hilton, 1992). Using the concepts of Dietrich et al. (1989), Lisle and Hilton (1992) found a relationship between the weighted mean V^* for reaches composed of multiple pools and a qualitative estimate of sediment supply based on land use. Areas with low levels of land use correlated with low V^* while areas with high levels of land use correlated with high V^* . Their Trinity Basin study quantified fine sediment in pools but did not measure actual sediment delivery due to land use.

The principles and measurement methods developed by Lisle and Hilton (1992) for determining downstream effects

of increased sediment supply were applied to the Pistol River Basin, supplemented by a detailed 50-year landslide and gully inventory to estimate dominant sediment production and delivery.

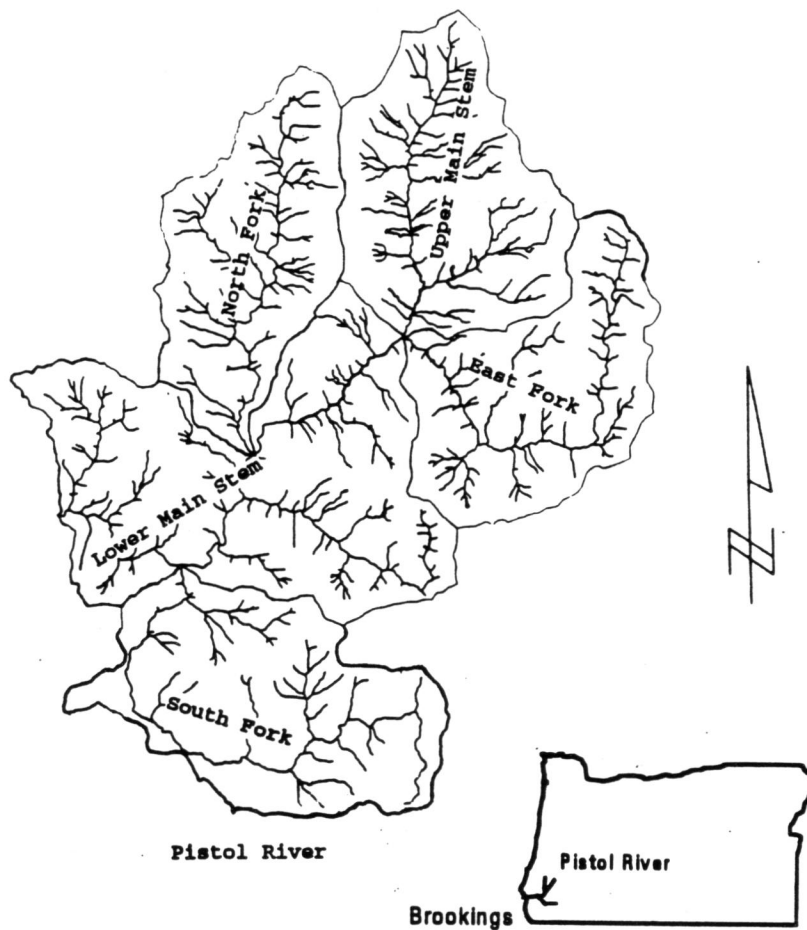
STUDY AREA

Location

The Pistol River Basin is located on the southwestern coast of Oregon and drains 387 km² directly into the Pacific Ocean (Figure 1). Five sub-basins totaling 220 km² and ranging in size from 34 km² to 64 km² were used for analysis. Ownership within the watersheds is distributed among Forest Service, BLM and private lands. Access to public land and residential private land was granted by the Forest Service and land holders but access to privately owned land was denied. Consequently, all field measurements were limited to Forest Service and residential land.

Pistol River Study Area

Pistol River, Oregon



Watershed	Area (km ²)
East Fork	36
Lower Main Stem	64
Upper Main Stem	40
North Fork	34
South Fork	44

Figure 1: Pistol River Study Area and 5 primary sub-watersheds shown with their areas.

Topography and Geology

Elevation in Pistol River ranges from 0 meters at sea level to 1286 meters at Snow Camp Mountain. Terrain is moderately steep and deeply dissected by steep-sided drainages. Most slopes are in the range of 0 to 40%, though 25% of slopes are greater than 40% (Figure 2). Pistol River is part of the Klamath Mountains geologic province and includes a mixture of igneous, metamorphic and sedimentary formations (Irwin 1966, Dott 1971, Jones and Ferrero 1990) (Figure 3, Table 1). Primary geologic units include Dothan and Colebrook formations. The Dothan formation dominates the basin and consists of mudstones, sandstones, shales and undifferentiated volcanics from the Jurassic period. They are similar to the California Franciscan formation. Soils in mudstone, siltstone and shale units tend to be deep (>1 m), silty and clayey, and poorly drained. Soils on sandstone tend to be sandy and well drained and of medium depth (.5-1 m) on slopes and thin (0-.5 m) on ridges. Dothan volcanics form outcrops or thin, rocky soils (Jones and Ferrero 1990). The Colebrook formation, also Jurassic, consists of low-grade metamorphic metasediments and metavolcanics (Diller 1966) predominately schist and phyllite with abundant quartz (Jones and Ferrero 1990). Soils are generally deep on moderate hillslopes and thin in steeper inner gorge and stream-adjacent slopes. Colebrook

soils are generally resistant to erosion on gentle slopes but are highly erosive on the steep inner gorges of stream channels. Cretaceous sediments have been mapped in the eastern part of the basin around Windy Valley and Windy Creek (Figure 3). Peridotite and serpentine dominate the upper slopes of the North Fork landscape though Colebrook Schists make up the inner gorges.

Several major fault zones have been mapped in Pistol River and include north/south trending, high angle reverse or low angle thrust faults. These faults form contact shear zones which subsequently act as groundwater conduits and form deep, sheared saturated soils (Jones and Ferrero, 1990). These areas are unstable when combined with steep slopes, and are an important source of sediment to Pistol River.

Mass movements in Pistol River are concentrated in the inner gorges and tributary headwalls underlain by Colebrook Schist and Dothan mudstone, siltstone and sandstone units and in contact zones. Landsliding is most prevalent in these over-steepened areas due to saturation as well as groundwater outflow along faults and contact zones (Jones and Ferrero 1990). According to Jones and Ferrero (1990), saturation by groundwater is a major cause of mass movement in all rock types, soils and slopes.

Slope Steepness Pistol River Basin

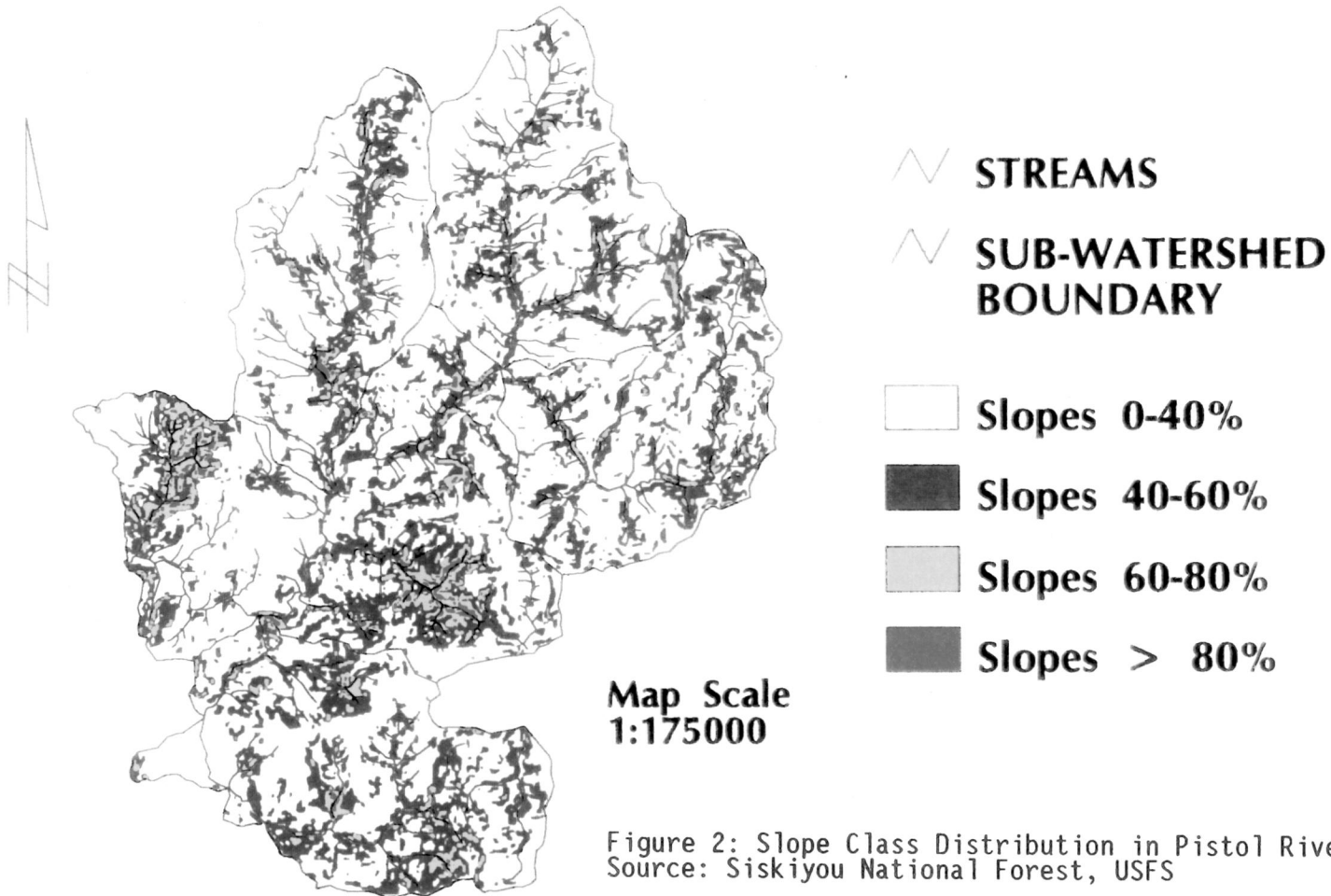


Figure 2: Slope Class Distribution in Pistol River Basin
Source: Siskiyou National Forest, USFS

Geology of Pistol River Basin

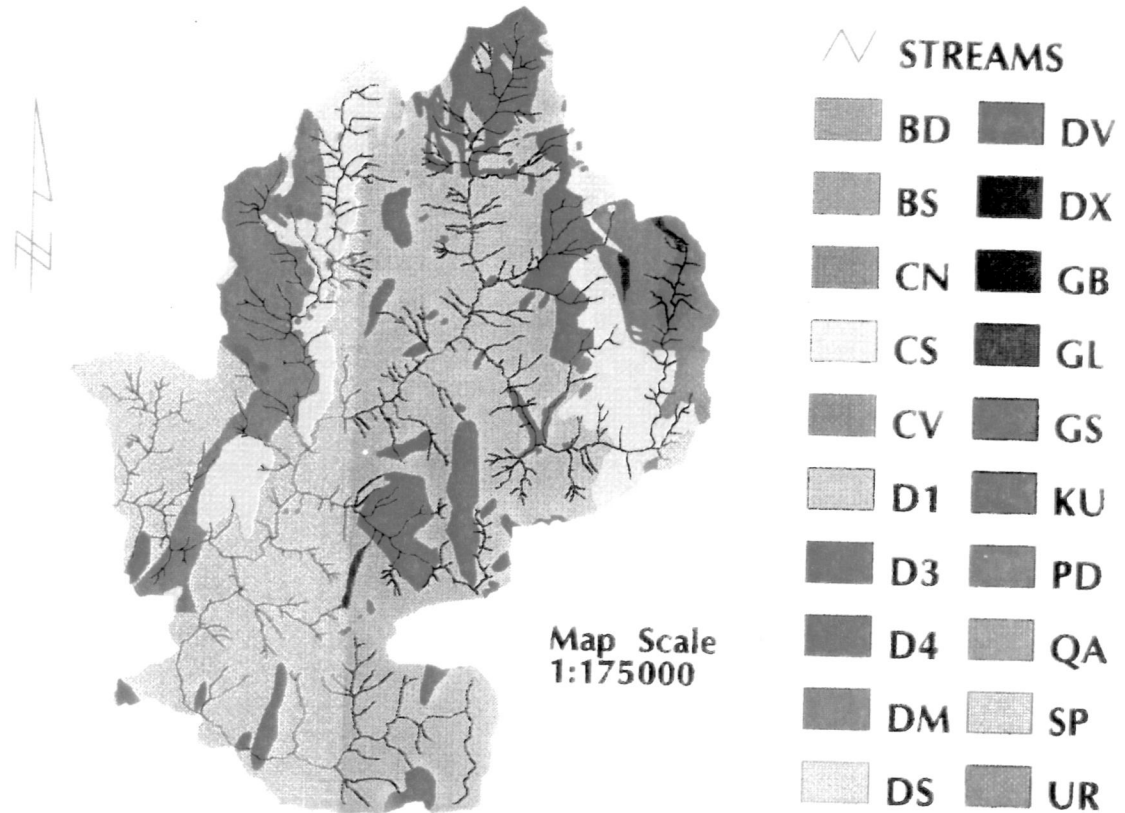


Figure 3: Geology in Pistol River Basin.

*The straight line left of center shows the division of detailed geologic mapping of Dothan units. Dothan has been mapped in detail on Forest Service land east of the line but has not been mapped west of line on private land.
Source: Siskiyou National Forest, USFS

Table 1: Legend for Geologic Formation Symbols
Pistol River, Oregon

SEDIMENTARY

- QA Quaternary alluvium
KU Cretaceous conglomerate, formation not identified

IGNEOUS

- GB Gabbro
UR Ultramafic rocks, undifferentiated
PD Peridotite
SP Serpentinite

METAMORPHIC

- DS Dothan Formation undifferentiated metasediments and
metavolcanics
D1 Dothan Formation zone 1, mudstone and siltstone
D3 Dothan Formation zone 2, greywacke sandstone
DV Dothan Formation metavolcanics rocks
DC Dothan Formation, chert
DX Dothan Formation, Dothan units sheared to complexity
beyond differentiation
DM Dothan Formation dominated Melange

CS Colebrook Schist metasediments, phyllite and schist
CN Colebrook Schist metaconglomerates
CV Colebrook Schist metavolcanics
BS Blueschist

Precipitation and Streamflow

There are no precipitation or streamflow gages in Pistol River. An isohyetal map obtained from the Oregon State University Extension Service (1982) describes estimated precipitation for Pistol River (Figure 4). Based on this map, average annual precipitation varies from 200 cm at the mouth of Pistol River to 350 cm at the upper northeast ridge of the basin. Peak streamflows for Pistol River were extrapolated from flow records at the U.S.G.S gaging station (1440000) located on the Chetco River located approximately 16 miles south of Pistol River (Park, pers.comm. 1992). A synthetic record from 1969-1991 was calculated by areally weighting discharges in Chetco River by the Pistol River drainage area. The 1955 and 1964 peak flows, were estimated for the Chetco River from high water marks on bridges and from evidence on aerial photographs and then extrapolated to Pistol River using the drainage area weighting method. Table 2 lists estimated peak flows for Pistol River. Average annual flow in Pistol River is estimated 1200 cfs based on the 30 year record from the Chetco gaging station.

Isohyetal Map Southwestern Oregon Coast

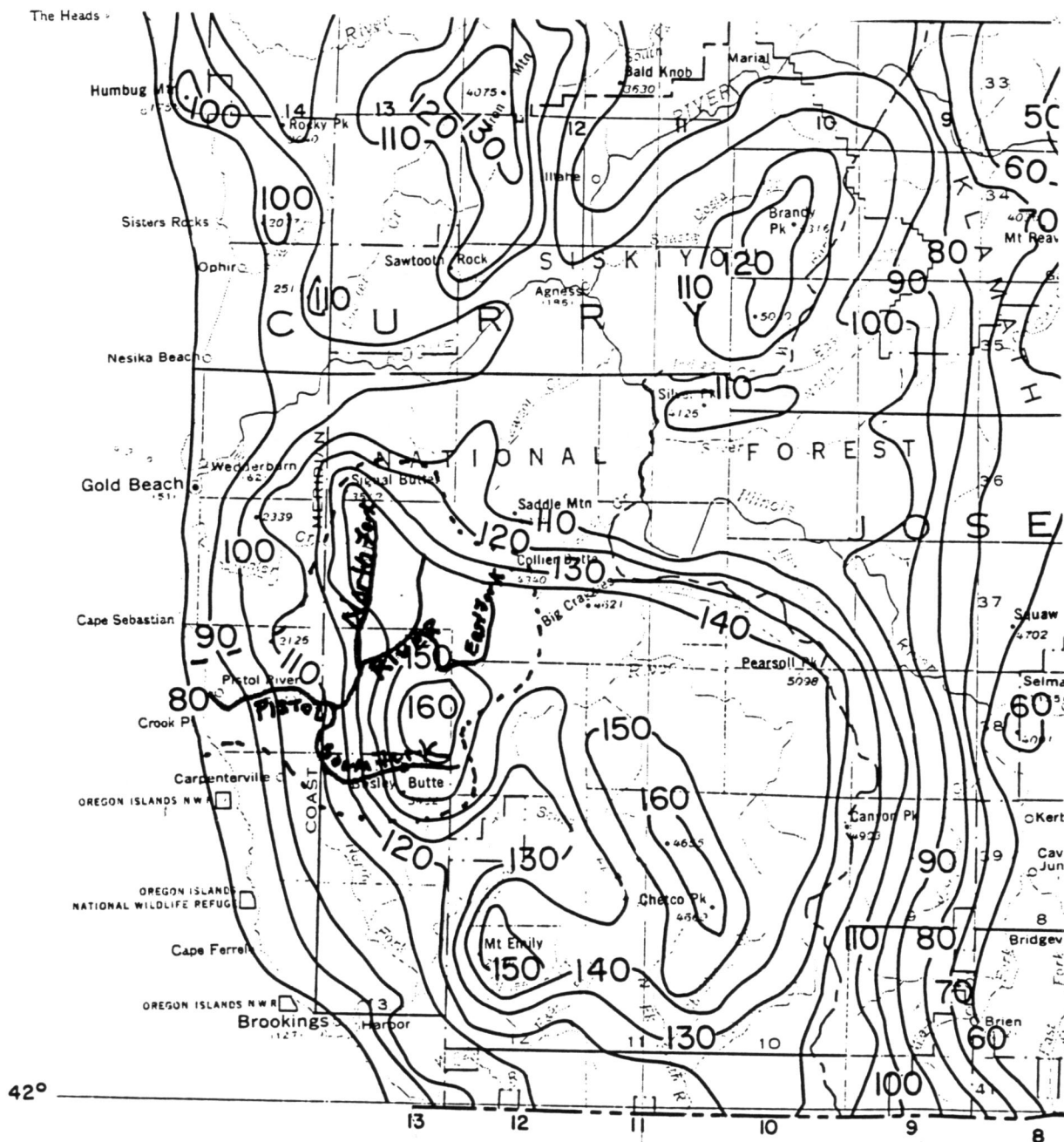


Figure 4: Isohyetal Map, rainfall shown in inches. Pistol River Basin is outlined.
Source: OSU Extension Service

Table 2: Estimated Peak Flows for Pistol River

Estimated by areally weighting Chetco River flows by Pistol River drainage area (387 km²)

<u>Year</u>	<u>Month</u>	<u>Avg Peak Flow (cfs)</u>	<u>Return Interval</u>
1955	Dec	31,300	>50 yr
1964	Dec	44,090	100 yr
1969	Jan	18,200	< 5 yr
1971	Jan	24,900	10 yr
1977	Dec	20,200	5 yr
1980	Dec	19,800	< 5 yr
1982	Jan	20,700	5 yr
1983	March	18,200	< 5 yr
1984	Feb	17,700	< 5 yr
1986	Feb	17,200	< 5 yr

Source: Chris Park, Hydrologist, Siskiyou National Forest, USFS

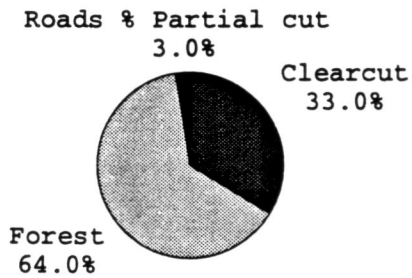
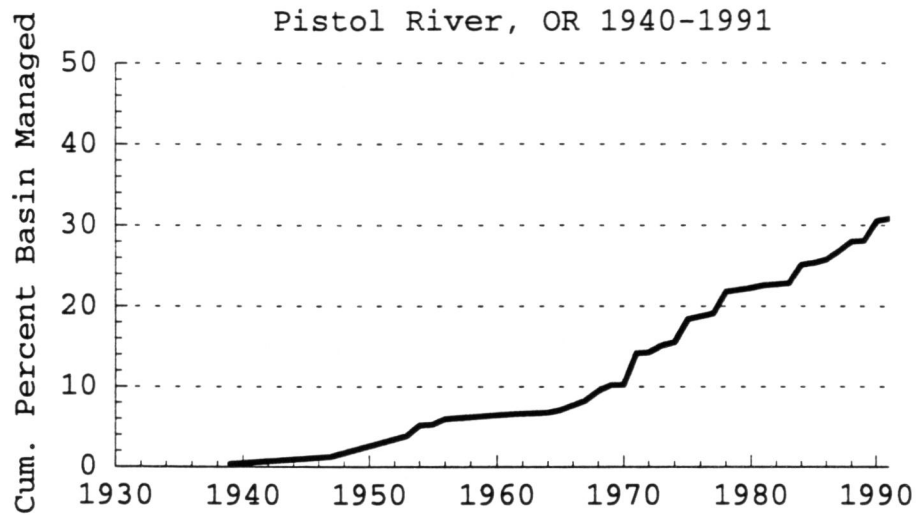
Vegetation

Vegetation on lower elevation hillslopes in Pistol River consists of a primary overstory of Douglas fir (Pseudotsuga menziesii) and a primary understory of tan oak (Lithocarpus densiflorus) and mixed shrubs of huckleberry (Vaccinium ovatum), salal (Gaultheria shallon), Pacific rhododendron (Rhododendron macrophyllum) and Oregon grape (Berberis nervosa). In upper elevations, dominated by ultramafic rocks, a variety of pines including sugar pine (Pinus lambertiana) and knobcone pines (Pinus attenuata), are present. Sadler Oak (Quercus sadleriana), manzanita (Arctostaphylos) and coffeeberry (Rhamnus californica) also reside in the dryer regions at higher elevations. Moist riparian areas in the basin consists of alder (Alnus rubra), big leaf maple (Acer macrophyllum), western sword fern (Polystichum munitum), golden chain fern (Woodwardia fimbriata), western azalea (Rhododendron occidentale), and occasional pacific yew (Taxus brevifolia). Port Orford cedar (Chamaecyparis lawsoniana) and incense cedar (Calocedrus decurrens) can be found in deep, wet toeslopes (Hickman ed., 1993).

Land Use History

Most timber harvest in Pistol River occurred within the last 50 years (Figure 5). In 1940, very little logging had taken place. Between 1940 and 1957, tractor logging began in the southern portion of the basin, leaving tractor road scars and skid trails still seen today. The rate of logging remained relatively low until 1969 and reached its peak between 1970 and 1986. In addition to logging, chromium and nickel mining were major activities in the 1950's, primarily in the upper North Fork Pistol dominated by gentle slopes and ultramafic rocks. Contribution of sediment from mining is considered low relative to that from logging activity.

Land Use Activity



Distribution of Land Use Areas as of 1991

Figure 5: Land Use Activity. Cumulative percent increase in basin area treated by management including road construction and timber harvest.

METHODS

Identification of Sediment Sources

Aerial photographs of Pistol River were obtained from the Siskiyou National Forest and Curry County for nine separate years between 1940 and 1991 (Table 3). Photographs were initially viewed with a stereoscope to identify dominant sediment sources in the basin. Identified sources included gullies, debris slides and avalanches, debris flows, slumps and earthflows. Debris slides, avalanches, debris flows and earthflow/slumps were characterized using established procedures for recognizing and mapping landslide types adapted by the Westside Engineering Zone II of the Siskiyou National Forest (1990) (Figure 6).

Table 3
List of Air Photographs for Pistol River, Oregon

YEAR	SCALE	TYPE(*)	SOURCE
1940	1:20,000	BW	Siskiyou Nat. Forest
1955	1:12,000	BW	Curry County
1956-57	1:12,000	BW	Siskiyou Nat. Forest
1964	1:12,000	BW	Siskiyou Nat. Forest
1965	1:12,000	BW	Curry County
1969-70	1:15,840	BW	Siskiyou Nat. Forest
1973	1:15,840	IR	Siskiyou Nat. Forest
1976-77	1:15,840	Color	Siskiyou Nat. Forest
1979	1:24,000	Color	Siskiyou Nat. Forest
1986	1:12,000	Color	Siskiyou Nat. Forest
1991	1:40,000	BW	Siskiyou Nat. Forest

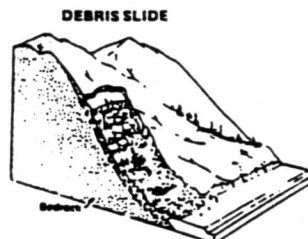
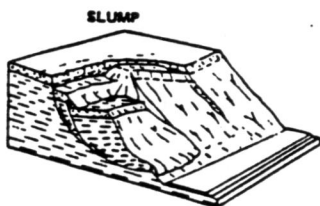
*BW=Black and White, IR=infrared

LANDSLIDE TYPES

Modified from Transportation Research Board Special Report 176:
Landslides Analysis and Control, 1978

Slides involve movement along one or several surfaces within a relatively narrow zone.

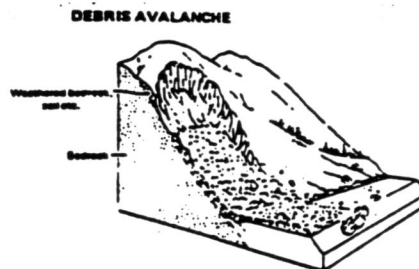
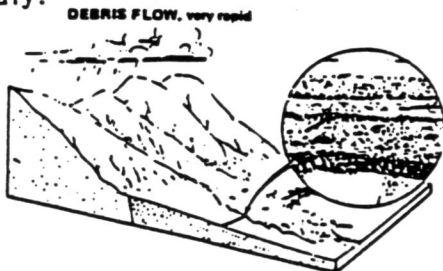
Debris slides (DS) are translational failures of debris which break up into smaller blocks as they advance toward the toe.



Debris slumps or simple slumps (SS) are rotational slides along a concave-upward surface.

Flows are distinguished from slides by increasing deformation and disintegration of material. Movement is not concentrated along discrete surfaces in flows. Debris flows (DF) have more than 80% coarse fragments (> 2 mm), and earthflows (EF) contain finer material.

A debris avalanche (DA) is a type of debris flow with very rapid movement, occurring on slopes steeper than 60%. Debris avalanches are generally long and narrow, and are commonly found along steep upland draws where they may fail repeatedly.



When a debris avalanche moves into an established stream channel, it may become a debris flow (or torrent). Guttled channels are the result of debris flows (DF).

Complex landslides such as slump-earthflows (SE) tend to be larger, deeper failures. A slump-earthflow fails as a slump from the headscarp and moves as a flow toward the toe.

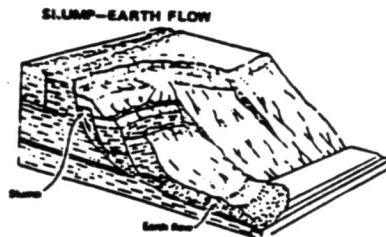


Figure 6: Landslide Classifications and Descriptions
Obtained from Siskiyou National Forest, USFS

Examination of photographs indicated debris slides and avalanches were the dominant mechanism of sediment production (Figure 7). Debris slides and avalanches were distributed throughout the basin in forested and clearcut areas, while gullies and earthflows were in isolated areas. Resolution of air photos limited visual detection to large gully erosion mostly seen in roaded areas where the canopy had been removed. Marginal gullies in earthflows could also be identified from photos as well as gullies within the earthflow interior. Field reconnaissance was done in canopy covered areas to detect gully and landslides not seen in air photos and is discussed later in this chapter. Very few debris flow tracks were observed on air photos.

Sediment Sources in Pistol River





Debris Slides and Avalanches - x
Earthflows - 
Gullies - 

Figure 7: Sediment Sources in Pistol River.

Landslide Measurements from Photographs

Aerial photographs were used to assess the areal dimensions of landslides in the basin. Each set of photographs was viewed with a stereoscope and all visible landslides larger than 100 m² were measured for length and width. Landslides less than 100 m² were too small to measure or identify accurately due to the resolution of the aerial photos. The area of each slide was measured using a scale accurate to 0.05 inches and then converted to meters depending on the scale of the photograph. To reduce the effects of radial distortion, area was measured at the most central location on the photo when possible. Slides were classified by failure type (Figure 6), as well as slope form, slope position and land use (Appendix A). Delivery of sediment to the closest stream was recorded by estimating the percentage of deposit, if any, left at the base of the slide. For example, slides that showed no evidence of a deposit were considered to have delivered 100% of sediment to the stream. If a deposit was present, a visual percentage was estimated based on the scarp above slide. Slides terminating on upper and midslopes were assumed to have not delivered any sediment to a stream.

Photographs were then compared to the next available photo set to estimate when landslides occurred. For example, if a landslide appeared on a 1957 photograph and

not on a 1940 photograph for the same area, the slide was assumed to have occurred between the years 1940 and 1957.

Landslide Volume Measurement

Three hundred ninety three landslides greater than 100 m² were identified in the aerial photographs. In order to estimate volume for each landslide, a relationship between photo measured area and field measured volume was developed for a sample population of landslides. This method for estimating landslide volumes has been successfully used in the past in several studies (Pillsbury 1976, Furbish 1981, McHugh 1986). McHugh's (1986) landslide inventory in the Elk and Sixes basins provided the primary model for Pistol River due to similarities in geology, topography, land use and geographical location. A sample of 40, approximately 10% of the total population, was randomly selected for field measurement. It was after the sample was selected that access to private land was denied, therefore, the sample was re-selected to include only slides on Forest Service land. During the course of field work, 6 slides proved to be inaccessible, therefore only 34 slides were field measured. These slides represented 8.5 percent of the total landslide population.

Landslide Field Measurement

Field measurements were obtained with a range finder accurate to 1 foot and a 200 foot tape measure. Slide length was measured along the longest axis extending from the headscarp of the slide to the toe. Width and depth were measured at the location on the slide best representing the average width or average depth. Depth measurements were visually estimated relative to the pre-slide ground surface. The slope of the adjacent hillslope was measured using an inclinometer. Slide type (Figure 6), slope position, and land use were recorded with the same guidelines used in photo interpretation (Appendix A). Percent stream delivery was visually estimated by subtracting the percent of the remaining deposit relative to the size of the slide from 100. If the deposit was delivered to the active channel but had not been eroded, it was considered delivered to the stream.

Measurement error between photo and field measured length and width of slides was estimated. Percent difference between photo measured and field measured slide length was 12% and photo measured width and field width was 2%. Stream delivery error was calculated in the same way resulting in a difference of 2%.

Landslide Area/Volume Relationship

The volume of all identified landslides was required to calculate a total sediment production volume due to landsliding. A simple regression model was used to obtain a relationship between field measured volume and photo measured area. Residuals from the regression model indicated the data to be lognormally distributed so the field volumes and photo areas were log transformed. The landslide volume/area resulted in the calibration equation:

$$\text{LOG}_{10} \text{ field volume} = 1.31 \text{ LOG}_{10} \text{ photo area} - .63$$

with an r^2 of .66 and $\text{STE} = .17$ (Figure 8). The resulting equation was then used to predict landslide volumes observed in photos but not measured in the field.

The r^2 value (.66) was lower than expected when compared to other studies (Table 4). Regression analysis between photo area and field area measurements alone yielded a more acceptable r^2 of .78, $p=.0001$ (Figure 9). Variability in this relationship is probably due to error in photo scales and/or by poor photo resolution in old or high altitude aerial photographs. Review of the data indicated older slides measured on older photographs produced greater error between photo and field measurements resulting in under prediction. However, the stronger area/area relationship indicated the variation in depth of field measured slides to have contributed the most to unexplained

variation in the volume/area model. While error in visually estimating depth of landslides may be a factor of the variability, the natural variation of depth of failures is also a contributing factor.

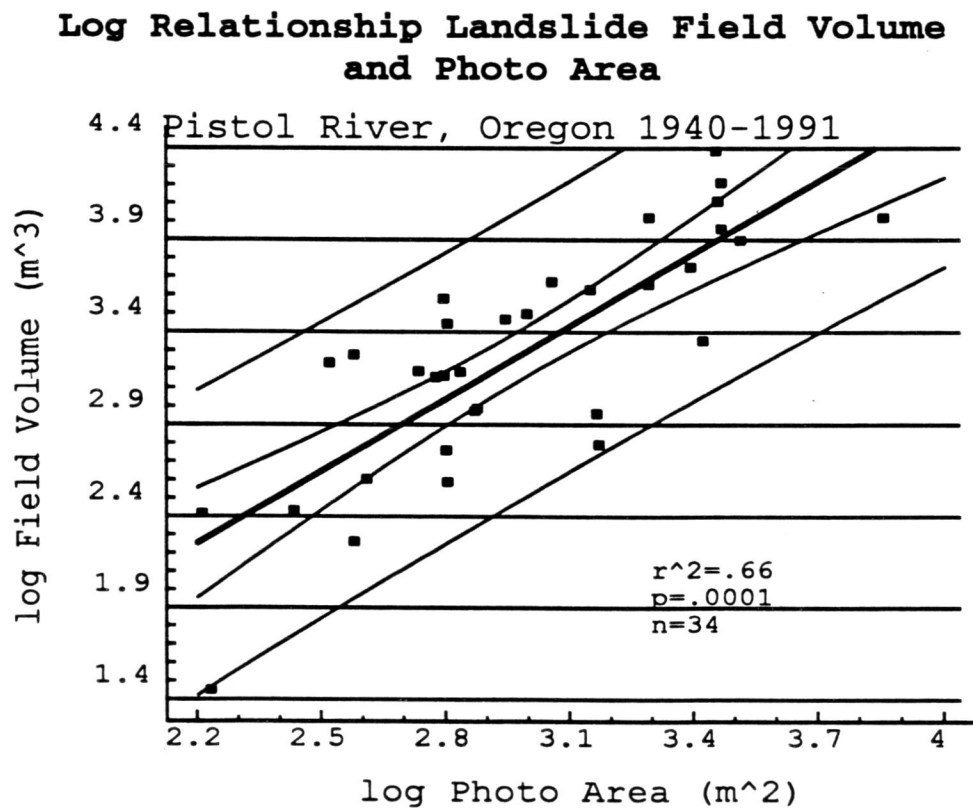


Figure 8: Regression of Landslide Field Measured Volume and Photo Measured Area

Once the landslides volumes were predicted using the regression equation, the log volumes were antilogged to obtain actual volumes. According to Ferguson (1986), statistical bias exists when back-transforming numbers based on least squares regression equations. Ferguson suggests that the predicted value from a log-log regression is the geometric mean rather than the arithmetic mean resulting in an inaccurate under-prediction. Due to this bias, the volume antilogs were subjected to a bias correction equation developed by Ferguson:

$$\text{True Volume} = \exp(2.65 * \text{pop. variance}) * (\text{predicted volume}).$$

Table 4: Comparison of Volume/Area Equations

Reference	Location	Geology	Equation	n	r ²
Furbish (1981)	Hurdygurdy-Jones N. California	metamorphic	$\log \text{fldvol} = 1.28585(\log \text{pharea}) - 0.51997$	16	0.95
Pillsbury (1976)	Little North Fork California	igneous	$\log \text{fldvol} = 1.03734(\log \text{pharea}) + 0.23039$	20	0.93
McHugh (1986)	Nooksack River N. Washington	metamorphic sedimentary	$\log \text{fldvol} = 1.14(\log \text{pharea}) + 0.0695$	18	0.87
McHugh (1986)	Elk-Sixes River SW Oregon	metamorphic intrusive sedimentary	$\log \text{fldvol} = 0.8795(\text{pharea}) + 0.72861$	55	0.87
Kelsey and Raines (1991)	Grouse Creek N. California	metamorphic igneous sedimentary	$\log \text{fldvol} = 1.13(\text{pharea}) + 0.821$	47	0.97
This study	Pistol River SW Oregon	metamorphic igneous sedimentary	$\log \text{fldvol} = 1.31(\text{pharea}) - 0.63$	34	0.66

Measurement of Other Sediment Sources

Gullies

Ten large gullies were observed and their length and width were measured on aerial photos. These gullies originated from non-maintained roads and in earthflow areas on public and private land. Access to gullies on private land was not possible so no field measurements were taken. However, seven gullies on Forest Service land were measured for length, width and depth using a range finder and a 200 foot tape measure. Length was measured by walking the distance of the gullies from the point of origin to where they joined a stream. Width and depth were measured at points where gully dimensions changed. Forest Service personnel also conducted an inventory of gullies originating from road culverts in Pistol River; these were included in the gully sediment production estimates. Gully erosion volumes represent the total sediment production from gully erosion over the 50 year study interval. Measurement of gullies was not traced through each set of photos since accurate detection of changes in width and length was not possible given the resolution of the photographs.

Earthflows, Slumps and Debris Flows

Seven large earthflows were identified in the Pistol River basin; five are located in the North Fork Pistol and two along the mainstem. Area of each earthflow was measured from photographs. Time constraints did not allow for field measurement on all 7 earthflows, therefore only two that appeared from photo evidence to be most active were field visited for ground truthing. The assumption was made that active earthflows were ones that most consistently produced and delivered sediment from landsliding and gully erosion in the past 50 years. Sediment production from landsliding and gullies in all seven earthflows was accounted for by photo measurement of the landslides at the toe and gullies within and marginal to the boundaries.

Four small simple slumps (Figure 6) were also identified and measured on the photos and in the field. Only one debris flow was identified from photos, so debris flows were not considered a dominate mechanism for erosion.

Canopy Cover Investigation

Five slope traverses were run in canopy covered areas to discover any erosional features not seen in the aerial photographs.

Five slides were found and their volumes were measured but there was little evidence of gullying found in these forested areas. These landslides were included in the landslide sediment production estimates.

ESTIMATES OF SEDIMENT PRODUCTION AND DELIVERY TO STREAMS

Sediment Production from Landslides

Landsliding produced an estimated 5,091,000 m³ of sediment over 50 years in Pistol River (Table 5). This estimate was calculated by summing all landslide volumes predicted by the regression equation. An estimated 86% of sediment produced by landsliding was delivered to stream channels in Pistol River.

Table 5: Sediment Production and Delivery Estimates
Pistol River, Or 1940-1991

Sediment Source	Total #	Production (m ³ /km ²)	Total Production (m ³)	Delivery Rate (m ³ /km ² *yr)
Landslides* and Simple Slumps	393	23,000	5,090,000	400
Gullies**	10	403	87,000	8.0

* includes landslides resulting from earthflows

** includes gullies within earthflow complexes

Absence of other major sediment sources as viewed on photos and in the field suggests landsliding to be the dominant source of sediment in Pistol River. This result is consistent with many other landslide inventories and sediment budgets conducted in the Pacific Northwest (Kelsey et al. 1981; Lehre 1982; McHugh 1986; Kelsey 1992). Kelsey and Raines (1991) conducted a sediment budget in Grouse

Creek, California having similar geology and topography as Pistol River and found landsliding to be the major source of sediment. In their study, Raines and Kelsey (1991) determined 86% of all sediment in Grouse Creek was delivered by landslides on hillslopes and streamsides while the remaining 14% was produced from streambank, gully, sheetwash and rill erosion.

Sediment Production from Earthflows

Landsliding from earthflows was included in the total estimate of landslide sediment production. Earthflows are slow, deep-seated soil mass movements generally five to ten meters in depth (Swanson et al. 1987). Earthflows present a complex mechanism of soil movement and erosion since their movement can produce debris sliding and gully erosion. Debris slides can result from oversteepening of the earthflow toe as the earthflow moves slowly down a slope. In addition to debris slides, streambank erosion at the earthflow toe may also occur as earthflows move into streams and are continuously eroded by stream flow. Gullies result along the margins of earthflows between stable adjacent slopes and the unstable earthflow when water collects in the margins and begins eroding soil in its path down hill. Within earthflows, gullies can develop when sections of the earthflow move at different rates than others. This complex

movement fractures the slope surface, water collects in fractures and cracks, and a gully develops. Seven earthflows were identified in Pistol River.

Two of the largest earthflows are located in the North Fork Pistol along Forest Service road 1503-030, one above the road and one below. This area is highly unstable due to a major fault resulting in complexly sheared Colebrook Schist (Figure 3). Movement rate of these earthflows was not estimated but both are active. Field observation revealed active marginal gullies along the earthflow boundaries and several smaller gullies within the earthflow complex as well as slumping and landsliding. The sediment produced and delivered from these gullies and landslides was accounted for in landslide and gully sediment production estimates. Activity in the lower earthflow was identified in the 1940 aerial photographs.

A large earthflow in the mainstem of Pistol River below the 3680-310 road was identified and field visited. Harvest and road activity in the area made estimates of sediment production from photographs difficult, but based on 1964 photos, the earthflow covers an area of .23 km². The numerous road related gullies developed within the earthflow were likely due to the combined effects of harvest, abandoned spur roads and earthflow movement. These gullies were measured and included in sediment production estimates

of surface erosion. Several smaller landslides were observed where the earthflow toe abutted the mainstem Pistol. These slides were accounted for in landslide sediment production and delivery estimates.

Sediment Production from Gullies

Contribution of sediment production from photo and field measured gullies was estimated at 61,000 m³ over a 50 year period by assuming an average gully depth of 1.5 meters. Average depth was estimated based on field measured gullies. Several smaller gullies observed in photos were not included in the estimate. However, a field survey of road related gullies conducted by the Forest Service concluded volume of sediment eroded from gullies formed at culvert outlets varied from 0 to 289 m³ averaging 77m³/km of road (USFS 1992) over the 20 km study area. Pistol River has approximately 347 kms of road, therefore road related sediment production from gullies at culverts over the basin is estimated at 26,000 m³. Forest Service estimates may only be used as a guide to road related gully erosion due to the high variability of the sampled data (Ricks, pers. comm., 1992) Based on Forest Service estimates and this study's estimates, sediment production from gullies is estimated at 87,000 m³. If added to the total sediment production from landsliding, gully erosion represents 1.7%

of total sediment production. Due the relatively low value of sediment along with the inability to assess gully erosion over time, gully erosion estimates were not used in the following sediment production analysis. Sediment production from gully erosion was estimated at 100% delivery to streams and these estimates, and landslide volume estimates, were used in stream reach analysis.

ANALYSIS OF SEDIMENT PRODUCTION AND DELIVERY FROM LANDSLIDING

Landslide frequency and corresponding rates of production have been the focus of several studies in the Pacific Northwest, especially comparisons between managed and forested rates (Table 6). Understanding mechanisms and processes related to landslides requires examination of the overall landscape in terms of geology, soil, slope, climate and land use. In Pistol River, landslides are analyzed over time with respect to geology, slope, storm events, land use and delivery. Sediment production from hillslope landsliding was addressed separately from landslide sediment delivery to streams in order to emphasize hillslope processes and factors controlling landslide vulnerability. Sediment delivery to streams as a fraction of sediment production on hillslopes was considered as a separate function from sediment production.

Landslides in forested areas are somewhat higher than most other studies in Pacific Northwest basins, but may be reasonably compared to the Grouse Creek, Ca. basin which has similar geology as Pistol River (Raines and Kelsey, 1991). Dothan and Colebrook Schist formations in Pistol River are structurally similar to the Franciscan and Galice formations in Grouse Creek (Irwin, 1966; Dott, 1971; Ricks, pers. comm., 1990). Raines and Kelsey (1991) reported

Table 6: Comparison of Estimates of Landslide Sediment Production in the Pacific Northwest

	Years of Study	Forest (m ³ / km ² *yr)	Harvest/ Clearcut (m ³ / km ² *yr)	Road (m ³ / km ² *yr)
Amaranthus et al (19??) Klamath Mountains	20	25.1	168	2742
O'Loughlin (1972) Coastal Mountains, Southwest BC	32	11.2	24.5	282.5
Swanson and Swanson (1977) Siuslaw NF, Oregon	40	32	62	1430
Hicks (1982) Middle Santiam River, Oregon	26	9.3	31.9	886
Marion (1981) Blue River, Oregon	34	37	322	1628
McHugh (1986) Klamath Mountains, Or	34	13	111	815
Morrison (1975) Alder Creek, Oregon	**	46	118	15764
This study Pistol River, Oregon	50	200	560	6440

** 15 yrs-managed, 25-yrs forested

that Grouse Creek sediment production is among the highest of published and available data for disturbed watersheds in the Pacific Northwest. The unmanaged rate of landslide sediment production in Grouse Creek was estimated from their published data at 675m³/km²*yr. Conversely, sediment production in Elk River, a basin 25 miles north of Pistol River, was much lower than in Pistol River, also due to geology. McHugh (1986) found the forested failure rate to be low considering the steep slopes and high precipitation

in Elk River. Landslide sediment production rates in Elk River and Grouse Creek were accelerated as a result of harvest and road construction, consistent with Pistol River (McHugh, 1986; Raines and Kelsey, 1991). Other studies have consistently shown roads to be a major cause of landslides, though it is unclear whether road-related landslides are a function of road construction methods or inherent slope stability (Table 6). It is important to consider the road area used in converting road miles to square kilometers. In Pistol River, 4 acres to the mile was used for conversion (Ricks, pers. comm., 1992). Many studies do not report road conversion factors so it is uncertain whether comparisons are equivalent.

Effects of Geology, Slope and Land Use on Landsliding

Past research demonstrates that reduction of shear strength in soils is the ultimate cause of mass failures (Schuster and Kirzek, eds. 1978). Underlying geology, soil depth and moisture, slope and hillslope vegetation are primary controls on shear strength. A comparison of landsliding on managed and forested hillslopes provides the means to determine how each factor affects slope stability in Pistol River (Table 7).

Slope steepness and vegetation removal appear to affect

slope stability within all geology units, however, Dothan metasediments (DS) and Dothan mudstones/siltstones (D1)

Table 7 Sediment Production and Frequency from Landsliding by Geology, Slope and Land Use Pistol River, Or 1940-1991

 Total Sediment Production (m³) X 1000 and (# of slides)

	<u>Harvest</u> m ³ (#)	<u>Road</u> m ³ (#)	<u>Forest</u> m ³ (#)
DS			
0-40%	751(30)	219(22)	387(23)
40-60%	318(40)	198(28)	229(15)
60% +	330(38)	278(22)	82(11)
DW			
0-40%	1(2)	603(2)	47(3)
40-60%	0(0)	0(0)	18(1)
60% +	116(6)	0(0)	0(0)
CS			
0-40%	82(1)	4(1)	25(4)
40-60%	0(0)	10(3)	132(9)
60% +	0(0)	0(0)	0(0)
CT			
0-40%	8(2)	8(2)	117(13)
40-60%	8(3)	230(2)	11(4)
60% +	36(7)	13(2)	4(1)
D3			
0-40%	13(1)	0(0)	3(2)
40-60%	21(4)	0(0)	29(4)
60% +	108(9)	3(1)	0(0)
D1			
0-40%	52(10)	97(2)	42(10)
40-60%	125(9)	29(7)	132(19)
60% +	12(6)	0(0)	16(2)
SU			
0-40%	0(0)	0(0)	104(3)
40-60%	7(1)	0(0)	0(0)
60% +	2(1)	0(0)	0(0)
VO			
0-40%	1(1)	2(1)	0(0)
40-60%	0(0)	0(0)	0(0)
60% +	15(3)	0(0)	0(0)
Total	2,006(174)	1,694(95)	1,390(124)

failed on all slopes in harvested and forested areas. A comparison of sediment production from landsliding by geology suggests Dothan sheared and melange (DW) rocks, Dothan metasediments (DS) and Dothan sandstone (D3) ranked highest in overall sediment production (Figure 10). While Dothan mudstone/siltstone ranked lowest, 10% of total landslide sediment production was in this unit due to the high percent of the landscape that it covers.

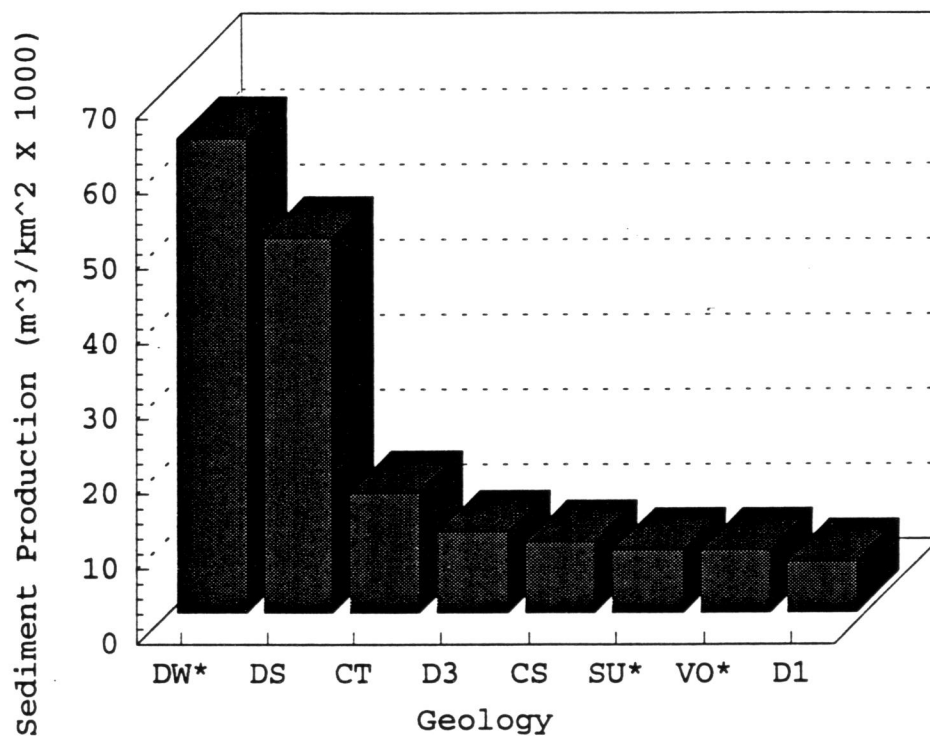
The spatial distribution of slope relative to geology was required to understand slope stability at the landscape scale. Using geologic and soil maps, and descriptions, (Irwin 1966, Dott 1971, Ricks pers. comm. 1990) along with the above table, geology was divided into 3 sub-groups of soft, intermediate and hard rocks. Sub-groups were determined by structural characteristics of the rock types, such as fracturing, spacing of discontinuities, degree of cementation in sedimentary rocks and texture. Slope was divided into 3 classes of 0-20%, 20-40% and >40% corresponding to low, moderate and steep slopes, respectively. A matrix was constructed for different combinations of sub-groups and a hazard rating of low, moderate and high was assigned to each matrix cell (Table 8). A distribution map were created and the landslide points were overlaid (Figure 11).

Table 8: Landslide Hazard Matrix used for Hazard Map Construction

Geology Sub-group	Geology	<u>Slope</u>		
		<20%	20%-40%	>40%
soft	D1, DM, DX, CT	moderate	moderate	high
inter- mediate	DS, CS	low	moderate	high
hard	DV, CV, D3, PD, GB, UR	low	low	low

**Sediment Production from
Landsliding by Geology**

Pistol River, Oregon 1940-1991



*DW=Dothan Melange and Dothan Sheared
 *SU=ultramafics, Peridotite and Gabbro
 *VO=Dothan and Colebrook Volcanics

Figure 10: Sediment Production by Geology. Sediment production was divided by area (km²) of underlying geology

Landslide Hazard Areas
Pistol River, Oregon

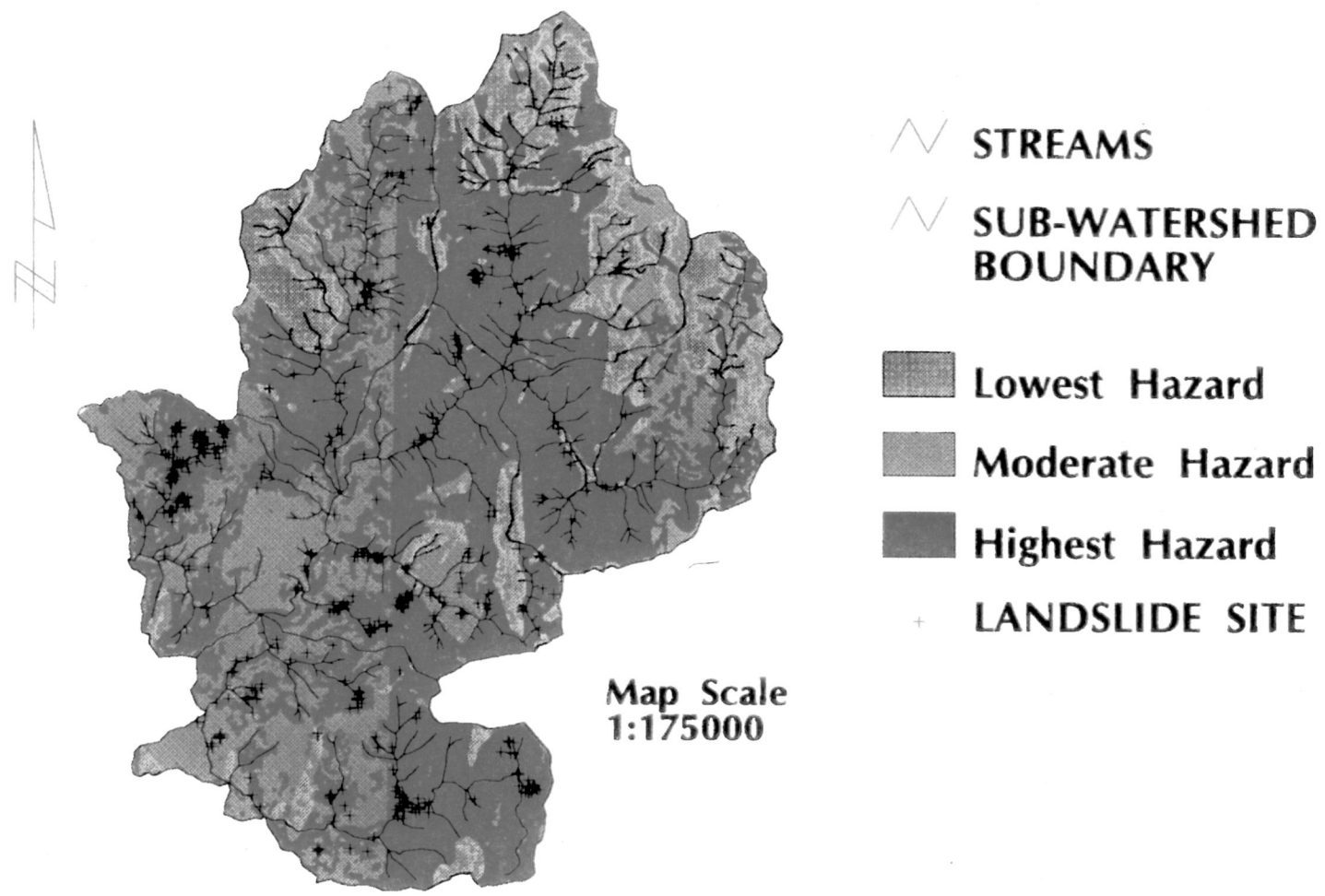


Figure 11: Landslide Hazard Map for Pistol River Basin.
Source: USFS

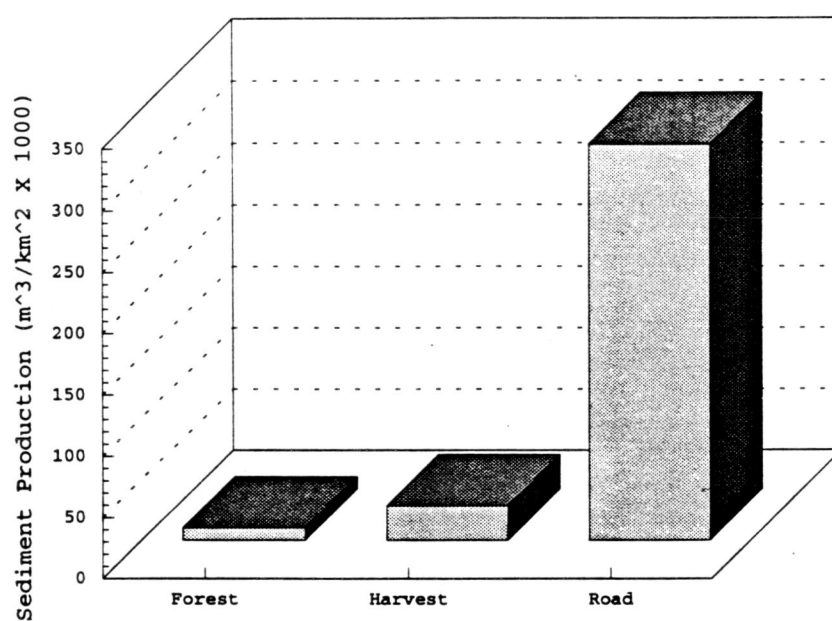
The hazard map indicates much of Pistol River consists of moderate to high landslide hazard zones, especially along inner gorge areas of streams consisting of mostly Dothan units and Colebrook Schist geology. Landslide occurrence on steep sloping Colebrook Schist terrain due to management activity is low, as seen in Table 7, because these areas are difficult to access and have experienced less management relative to more accessible areas. Most landslide sediment production that did occur under natural conditions on Colebrook Schist was initiated from steep slopes in inner gorges of the North Fork Pistol. Many of these steep slopes are the result of earthflow movement causing over-steepening of toe-slopes. Low hazard zones exist along the outer edges of the basin and in isolated pockets within the basin interior. Low hazard areas correspond with ultramafic, volcanic rocks and low sloping Dothan sandstone that generally are resistant to landsliding unless management had taken place.

Landslide Sediment Production and Frequency by Land Use Area and Time

Landslide rates by land use and time were analyzed. Timber harvest increased sediment production from

Sediment Production from Landslides by Land Use

Pistol River, Oregon 1940-1991



Landslide Sediment Production

Land Use	m^3/km^2	$m^3/km^2 \cdot yr$	relative to forest rate
Forest	10000	200	1X
Harvest	28000	560	2.8 X
Road	322000	6440	32 X

Figure 12: Landslide Sediment Production by Land Use

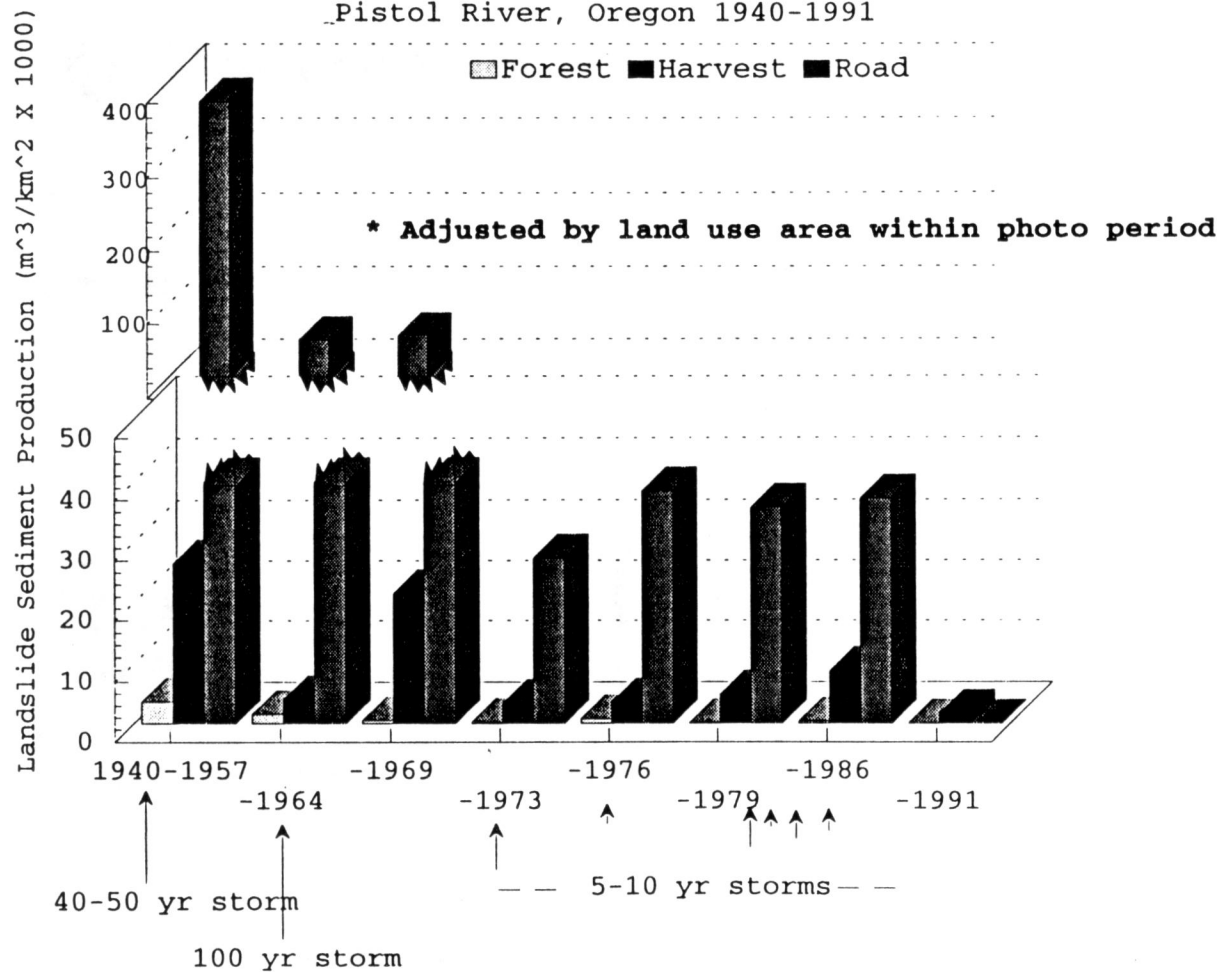
landsliding over forested rates by a factor of 2.8 times while road construction increased rates by 32 times (Figure 12).

The addition of time to the analysis indicates that sediment production from forested areas decreased as production from managed areas increased (Figure 13,14). Sediment production increased with the amount of area managed, timing of storms, and entry into more difficult terrain. McHugh (1986) had the same result. For example, the increase in landslide sediment production in harvested areas between 1979-1986 is coincident with clear cuts on Dothan metasediments and sandstone on slopes averaging 60%. This time period also includes several storms with 5-10 year return intervals. However, the increase in the number of slides during this period relative to the sediment produced is not consistent with other time periods. The majority of these landslides were concentrated in a small sub-watershed on private land in the lower main stem and were, on average, much smaller in volume. Overall, there is a decreasing trend in sediment production from landsliding in both managed and forested areas. The highest sediment production corresponds with large storms early in time. The absence of large storm events combined with better land use practices later in the time period may be reflected in the decreasing trend.

Lag time between harvest and road activity and landslide occurrence was not analyzed. However, the total land use shown in Figure 13 was cumulative through time. It is safe to assume that all landslides did not occur immediately after road construction and harvest had taken place. Observation of the year of harvest and road construction on Forest Service land compared to the year of landslide occurrence revealed that older units and roads were continuing to fail long after initial vegetation removal. Newer units and roads appeared to be failing less often. This observation may be the result of improved land use practices, especially in road construction methods.

**Total Sediment Production from Landsliding by Land Use
and Photo Year***

Pistol River, Oregon 1940-1991



**Figure 13: Landslide Sediment Production by Land Use Area
and Photo Year**

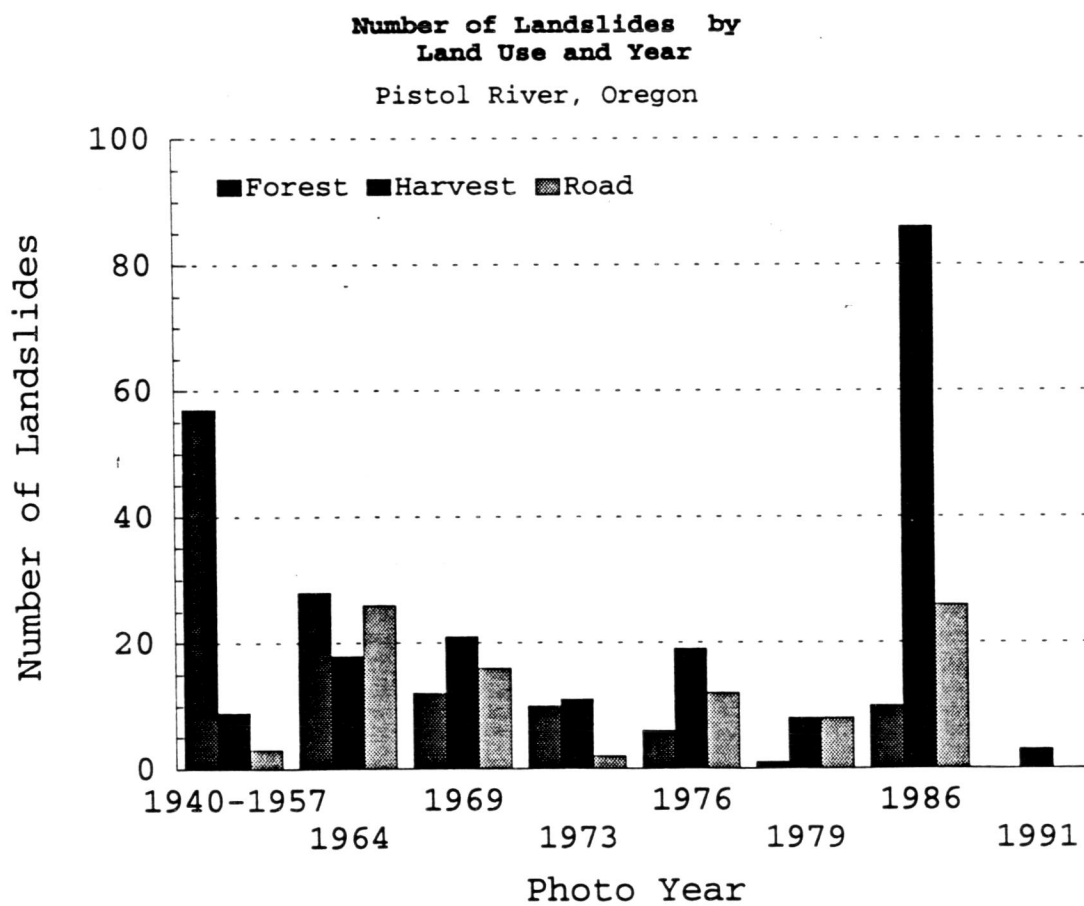


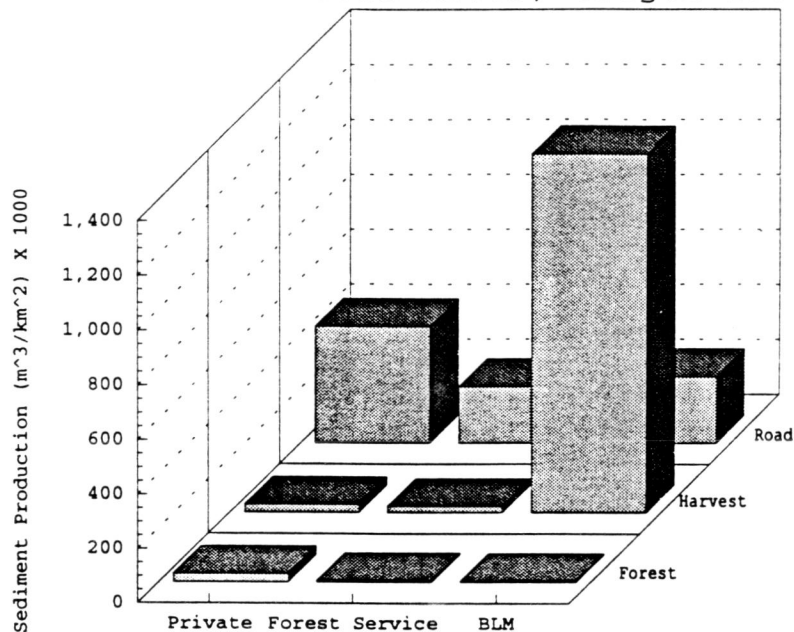
Figure 14: Number of Landslides by Land Use and Photo Year

Sediment Production by Land Use and Ownership

Land use ownership in the Pistol River Basin and related land use sediment production was analyzed (Figure 15). The total amount of sediment produced from landsliding on private land is generally higher than Forest Service land on both managed and unmanaged landscapes, while BLM has the highest sediment production rate from landsliding. Higher rates may be attributed to different harvest and road construction methods and harvest unit size. However, much of the total area within BLM and private land boundaries lies in unstable terrain with high landslide vulnerability (Figure 16). Even without land use, these areas are prone to failure due to steep slopes and the abundance of Dothan metasediments. Landslide sediment production in the South Fork Pistol River for private land may also be over-estimated since a portion of this land was obtained from the Forest Service several years ago. Information concerning the precise year and area of the exchange was not available, so land ownership area was based on current information.

**Sediment Production from
Landsliding by Land Use
and Ownership**

Pistol River, Oregon 1940-1991



	Private	Forest Service	BLM	TOTAL LAND USE RATE
FOREST	620	120	80	200
HARVEST	600	480	26220	560
ROAD	8500	4120	4860	6440
TOTAL OWNERSHIP RATE	960	280	280	480

Figure 15: Landslide Sediment Production by Land Ownership. BLM harvested land produced the greatest amount of sediment from landsliding at the highest rate. However, private land experience the greatest overall rate for all land use classes.

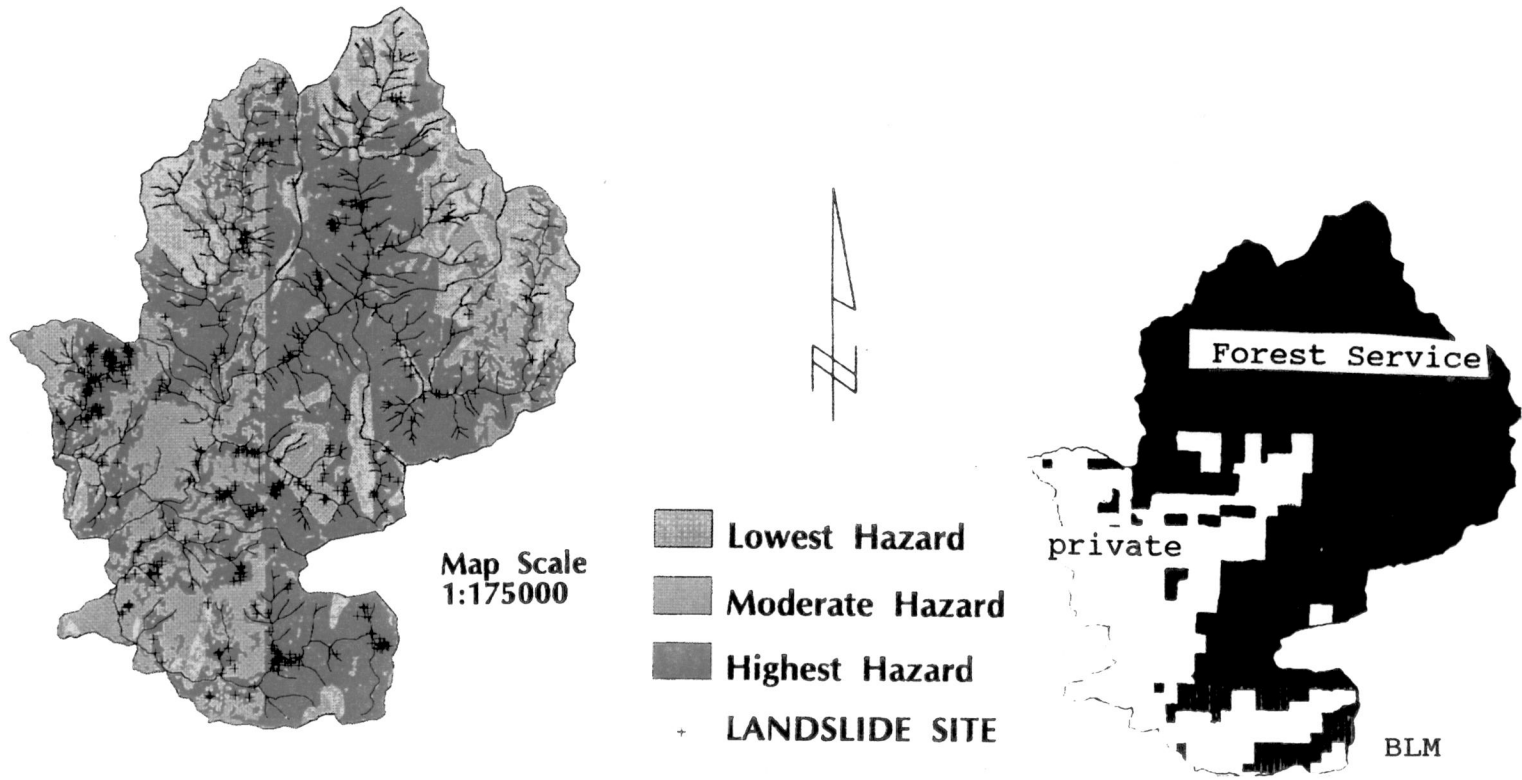


Figure 16: Landslide Hazard Map with Ownership Boundaries. Much of the private and BLM owned land consists of steep inner gorge slopes and weak-intermediate strength geology.

Estimated Landslide Sediment Delivery to Channel

Approximately 86% of 5,090,000 m³ of sediment produced from landsliding over the period 1940-1991 was delivered to Pistol River; this translates to an average delivery rate of 400 m³/km²*yr. Sediment delivery from landslides to streams was most influenced by slope position and geology in that the more frequent streamside slides on Dothan and Colebrook Schist delivered 100% of their material to streams (Figures 17) Area of each slope position was not available, but the assumption can be made that the landslide sediment delivery rate was higher on stream adjacent slopes than upland or midslopes. The area of stream adjacent slopes is relatively small compared to the area of the remaining basin. As previously noted, Raines and Kelsey (1991) reported streamside slides were most common in Grouse Creek. Mid-slope slides delivered sediment to streams when they failed at stream crossings.

Harvest and road activity may have accelerated the rate at which landslide sediment was delivered primarily due to the location of management activity above and along streamside slopes. The sediment delivery rate from harvested slopes increased over the forested rate by a factor of 2.8, the same as the production rate. However, the road related sediment delivery was less than the production rate by a factor of 4. Comparison of land use

and landslide sediment delivery shows that delivery increased as management increased (Figure 19). Increases in delivery corresponded with large storms early in the study period, but were not consistent with the magnitude of more frequent storms after 1964. For example, 65% of road related sediment delivery occurred between 1940 and 1969, time periods which include the 1955 and 1964 storms, while harvest related sediment delivery was most affected by the storm in 1964, and 4 smaller events between 1979 and 1986. Harvest was not as common as road construction in 1955, but had increased by 1964.

Sediment delivery in Elk River was much lower than Pistol River and averaged $56 \text{ m}^3/\text{km}^2\cdot\text{yr}$. Landslide sediment production in Elk River was estimated at $620,000 \text{ m}^3$, with about 60% delivery (Ricks pers. comm., 1992). Even though Elk River has abundant steep slopes, geology in the area is competent and weathers slowly (Ricks, pers. comm. 1990). The Elk River study did not evaluate landslides in terms of slope position, but it is possible that streamside debris slides were not common.

**Sediment Delivery from Landslides by
Slope Position**

Pistol River, Oregon 1940-1991

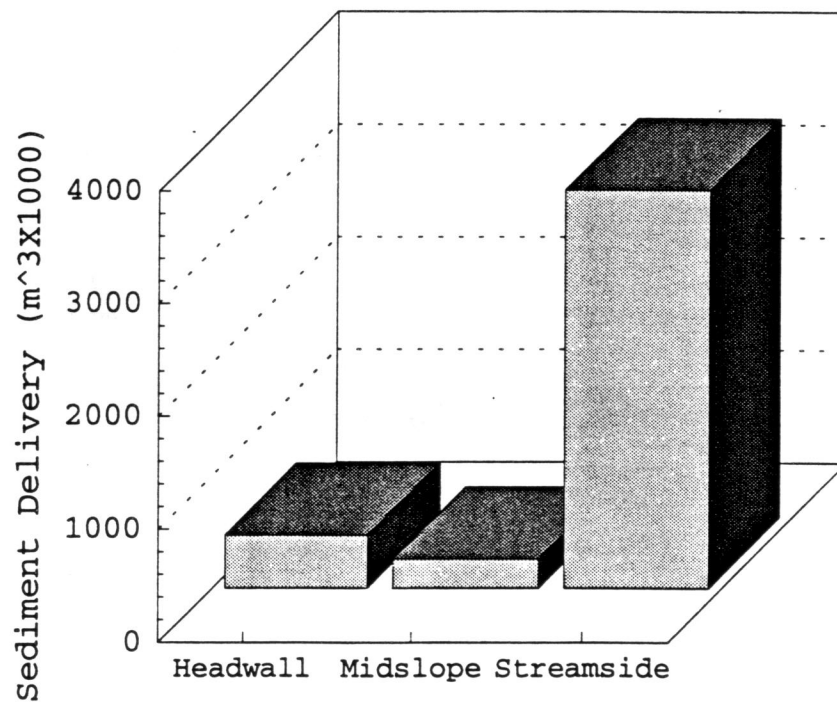
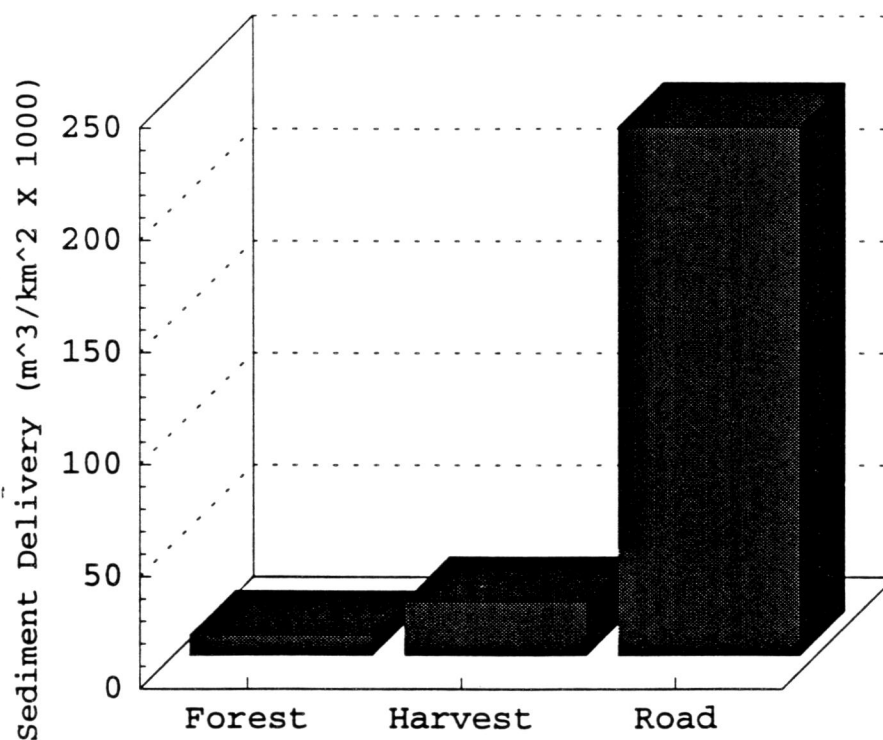


Figure 17: Landslide Sediment Delivery by Slope Position

Landslide Sediment Delivery by Land Use
Pistol River, Oregon 1940-1991



Delivery Rates by Land Use:

Forest - 170m³/km²*yr

Harvest- 480m³/km²*yr

Road- 4700m³/km²*yr

Figure 18: Landslide Sediment Delivery by Land Use

Comparison of Cumulative Percent Increase in
Land Use Area and Sediment Delivery

Pistol River, Oregon

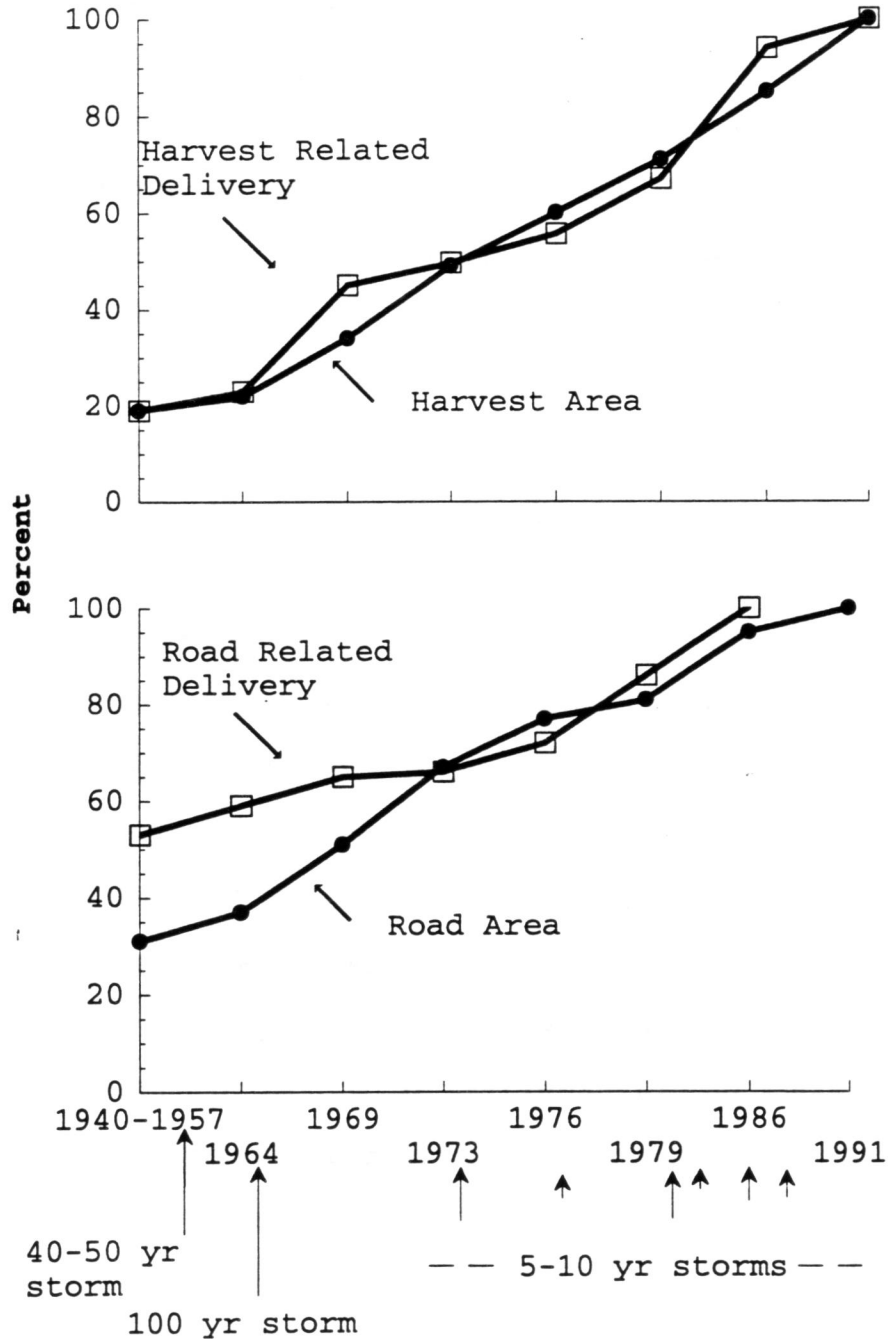


Figure 19: Comparison of the Increase in Land Use and the Increase in Landslide Sediment Delivery by Photo Year

The Lower Mainstem and South Fork Pistol River watersheds received the majority of sediment in the basin (Figure 20). Most sediment was delivered into first through fourth order streams rather than the main channels (orders 5 and 6). Both of these areas are dominantly Dothan metasediments, siltstone/mudstone and sandstones and have experienced the greatest concentration of harvest and road activity. Lower Mainstem Pistol received approximately 40% of all landslide-delivered sediment in Pistol River (Figure 21). This watershed includes Deep Creek and a tributary to Sunrise Creek which were logged after 1979, as seen in the delivery increase between 1979 and 1986. The South Fork and Lower Mainstem Pistol River were the initial areas of entry for timber harvest due to their low elevation and location and have consistently had the highest management rates. Ownership in these watersheds is shared between BLM, Forest Service and private. The East Fork Pistol received the lowest percentage of sediment delivery from landsliding and has had the least management activity even though slopes are steep and underlain primarily by Dothan siltstone/ mudstone and Colebrook Schist. Sediment delivery in the East Fork occurred between 1940 and 1969, primarily on stream adjacent slopes.

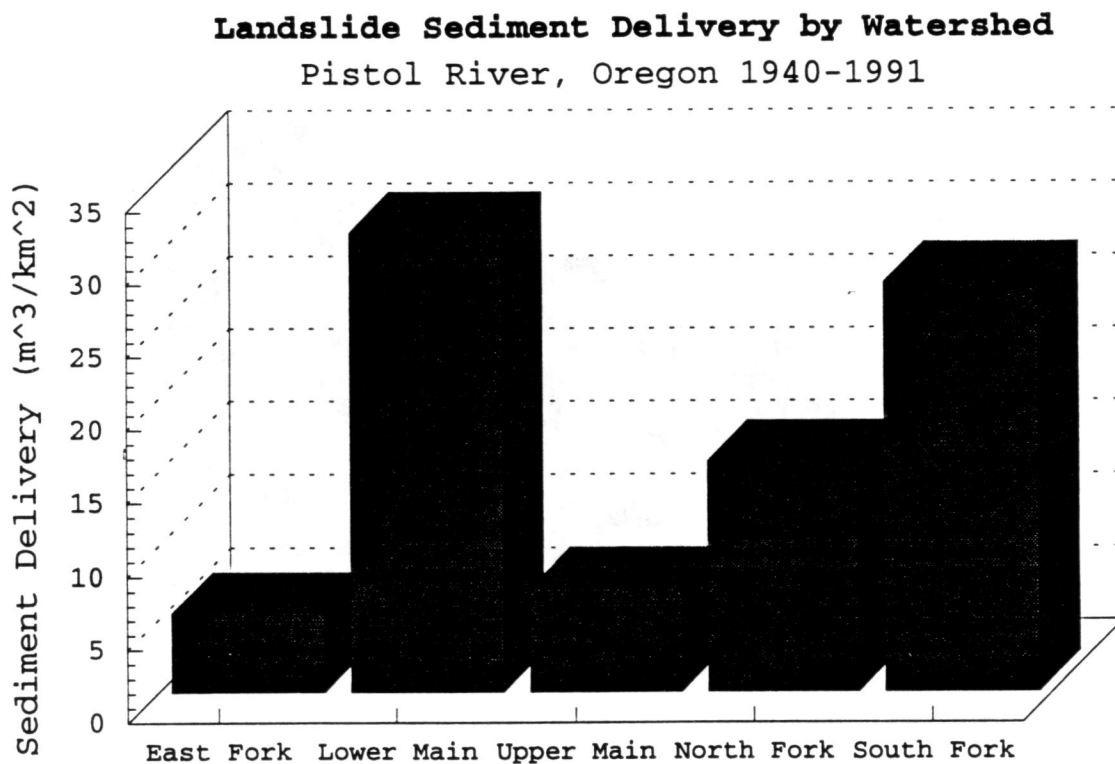


Figure 20: Landslide Sediment Delivery by Watershed Area. Delivery in each watershed was divided by the watershed area to determine total delivery to each watershed.

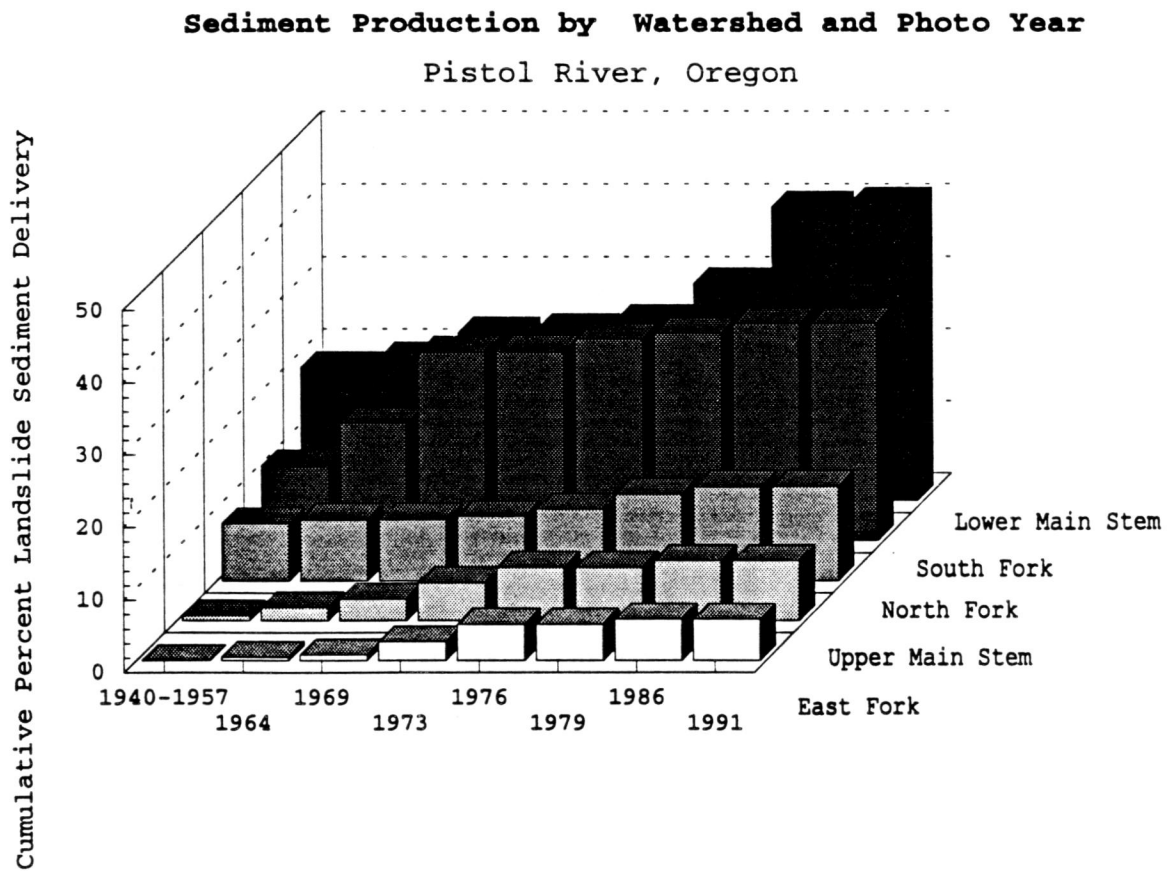


Figure 21: Cumulative Percent Landslide Sediment Delivery by Watershed and Photo Year

FACTORS INFLUENCING FINE SEDIMENT PRODUCTION AND DELIVERY FROM LANDSLIDES

Sediment Production

The landslide inventory analysis indicated that both Dothan and Colebrook Schist formations, and contact zones were most susceptible to failure along streamside slopes and produced and delivered most of the fine sediments in Pistol River. Analysis also indicated that the largest volumes of delivered sediment were coincident with large storms early in the time period. The next big pulse of sediment delivery was between 1979 and 1986. The landslides producing this sediment were abundant, but were smaller in size in comparison to other years.

Sediment delivered from landslides in unstable geologic formations in Pistol River consisted of fine-grained material and introduced sediments of sand-sized particles or smaller (<2mm) to streams. Boulder and cobble sized sediments were also mobilized during landslide events but were usually observed at the base of the slide or in the adjacent stream. Gravel was also observed in the channel. Fine sediment from landslides was only observed when it had not reached the channel suggesting that fine sediment entering the stream was transported downstream.

It is these sediments that are of greatest concern to fisheries since they tend to deposit in pools and riffles.

The following sections attempt to link fine sediment delivery from landsliding to the stream channel by examining pool response in Pistol River.

EFFECTS OF LANDSLIDE SEDIMENT DELIVERY ON POOLS

Introduction

Sediment delivery to streams from landslides can change fish habitat. The specific changes in channel morphology can be damaging to fish habitat by deposition in areas necessary for rearing and spawning, but changes are not always detrimental. There are some indications that sediment delivery to streams may actually improve habitat, depending on the grain size of delivered sediment. For example, large gravel and cobble sized sediments have been found to add stream structure to areas previously consisting of silt and sand, thus adding suitable spawning habitat (NCASI Technical Bulletin, 1985). Sediment can also add to channel stability when it is deposited along stream banks and re-vegetates to provide root strength to soils and shade to streams (Chesney, 1982). Positive or negative changes to streams are dependent on hillslope geology, the percentage of fines delivered, discharge and location of deposits relative to existing channel structure (Stack, 1988). Moreover, long term negative changes are dependent on when and where sediment is delivered to streams and where it is routed. Sediments delivered to streams in Pistol River consist of high volumes of fines as previously described. Time analysis indicated that the majority of

fine sediment was delivered in large quantities most often directly from streamside slopes over relatively short intervals. The following analysis was conducted to determine if the downstream effects of this sediment delivery could be detected by examining fine sediment deposition in pools.

REACH AND POOL SELECTION AND MEASUREMENT

Pool volumes and sediment storage were measured in eight stream reaches (Figure 22). Reaches were selected based on channel slope, sediment supply and discharge. It was assumed that reaches with gradients of .02-.05 tend to store more sediment than higher gradient reaches and would be sensitive to changes in sediment delivery (Lisle and Hilton, 1992). Slopes were initially inventoried and estimated using USGS topography maps but were calculated from measurements on controlled photos using a stereoplotter. After slopes less than 5% were inventoried, sediment delivery estimates from landslide sediment production analysis and drainage areas above the reaches were ranked. Drainage area was included in the selection criteria since it was assumed to be proportional to discharge and hence, stream power. Reaches were then chosen to represent a range of sediment deliveries and drainage areas to examine pool/reach response to these factors over the past 50 years (Table 10). Because this study incorporated an entire basin, the reaches are nested in that downstream reaches are influenced by upstream reaches. Only reaches 1, 5 and 7A are totally independent. The remaining reaches were chosen due to changes in sediment supply above and below them.

Pistol River Sample Reaches

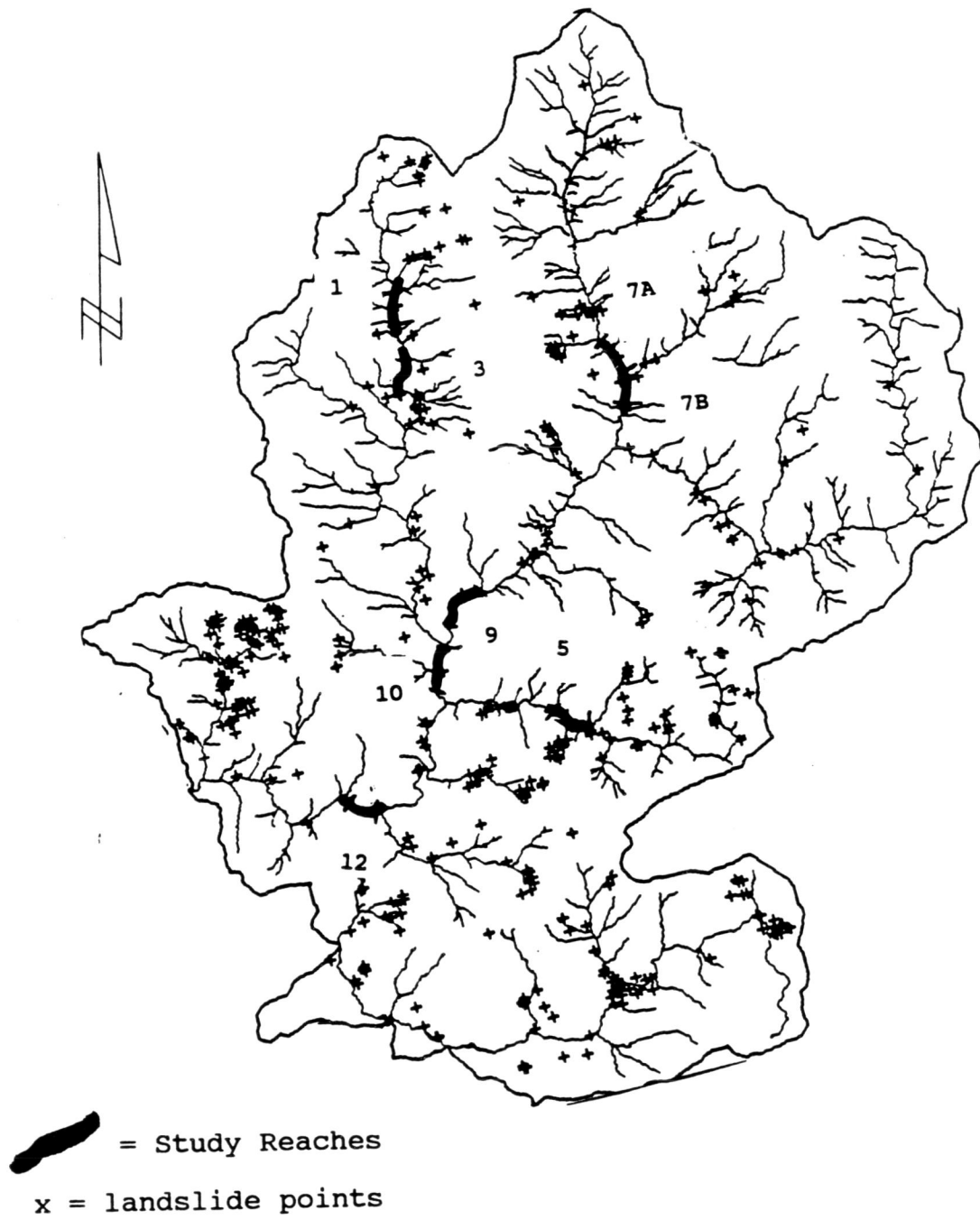


Figure 22: Pistol River Sample Study Reaches

Sediment delivery to each study reach ranged from 166,000 m³ at the uppermost reach to 2,670,000 m³ at the lowest reach in the basin and included landslide and gully delivered sediment. Since the transport distance of sediment is unknown, it was assumed that delivery into upper regions of the basin contributed to all reaches below that point. Therefore, sediment delivery to reaches are cumulative totals of upstream sediment delivery during a 50-year period.

Table 9 - Stream Reach Criteria

Reach	Total Delivered Sediment (m ³)	Slope (%)	Drainage Area (km ²)
1	166,000	4.0	8.3
3	296,000	4.0	18.9
5	201,000	5.0	11.0
7A	203,000	4.0	24.6
7B	250,000	2.5	36.0
9	582000	1.5	91.5
10	934,000	1.8	127.0
12	2,670,000	1.0	220.0

Residual water volume and fine sediment volume were measured in 4 to 15 pools in each reach during summer low flows in 1991 and 1992 (Bathurst 1981; Lisle 1986, Lisle and Hilton, 1992). Residual volume of a pool is defined as the pool volume below the elevation of the downstream riffle crest and therefore is independent of discharge. (Figure 23). (Lisle and Hilton, 1992). Pool volumes in two reaches

were re-measured in summer 1992 to compare to the previous summer and were found to be within 85% of previous volumes. The 15% difference between summer 91 and 92 was attributed to measurement error and year to year variability. The study by Lisle and Hilton (1992) indicated 10-15 pools within a reach were needed to adequately represent the variation of water and sediment storage in pools. However, access to private land in reaches limited the number of pools that could be measured. A pool within a reach was selected for measurement if it was at least a stream width wide and a stream width long.

Water and fine sediment depth were measured at cross sections oriented perpendicular to flow and spaced at 10 foot intervals within the pool. All measurements were taken using a 200 foot tape and a .5 inch graduated steel rod. Water depth was recorded and the rod was pushed into the bed until the gravel or boulder surface was reached. The depth was recorded and subtracted from the water depth to obtain the depth of fine sediment.

The index of fine sediment volume in a pool, V^* , was calculated as the fraction of scoured pool volume occupied by fine sediment, $V^* = V_f / (V_f + V_w)$, where V_f is the volume of fine sediment and V_w is the volume of water. Scoured pool volume, $V_f + V_w$, is the residual volume of the pool when the fine sediment is removed (Lisle and Hilton 1992).

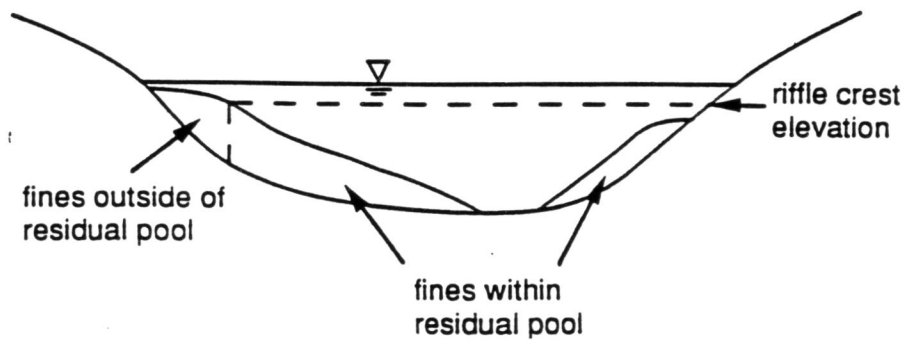
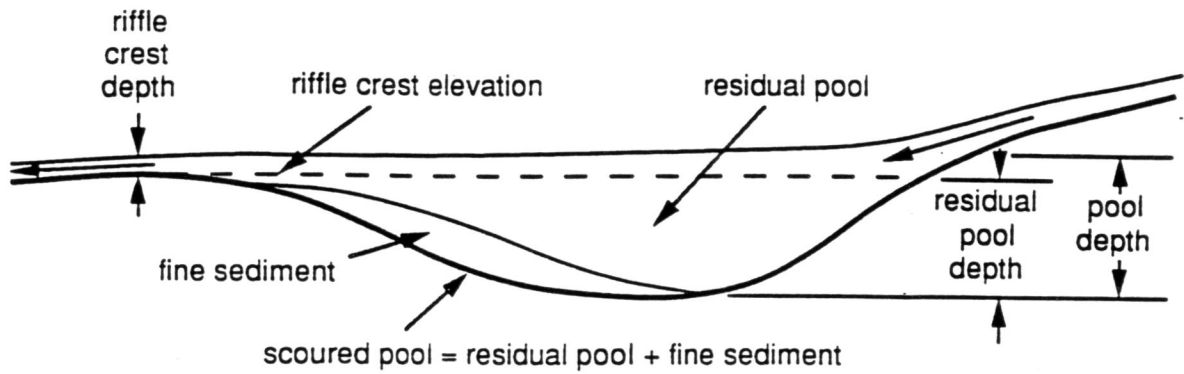


Figure 23: Diagram of Residual Pool Volume and Fine Sediment.
 Source: Lisle and Hilton (1992)

The mean V^* value for each reach was calculated as a weighted mean:

$$V^*(\text{mean}) = (V_f)/(V_f+V_w).$$

All volumes and reach V^* s were calculated using a spreadsheet application provided by Sue Hilton of the Pacific Southwest Research Station (1993).

EFFECT OF HILLSLOPE SEDIMENT DELIVERY ON POOL VOLUMES AND STORAGE

Fine Sediment Storage in Pools

Fine sediment in pools was primarily stored on edges and downstream ends of pools where shear stress is typically less than at pool heads and along the thalweg. Percent of fine sediment ($V^* \times 100$) ranged from 3% to 43% in the 69 measured pools, and 37 pools had V^* values greater than or equal to 15%. Average percent of fines among all pools equalled 17%. A strong positive correlation was found between total fine sediment volume and scoured pool volume (Figure 24), suggesting that larger pools have the capacity to store larger amounts of fine sediment. However there was no significant correlation between percent of fine sediment in pools (V^*) and scoured pool volume indicating that the percent of fine sediment is independent of pool size (Figure 25).

Fine Sediment in Reaches and Delivered Sediment

When V^* was first regressed against total delivered sediment for each reach, a negative correlation ($r^2 = .60$) was found (Table 11). Total delivery was

Table 10: Reach Data

Reach	Mean V*	Drainage Area (km ²)	Total Delivered Sediment (m ³)
1	.21	8.3	166,000
3	.18	18.9	296,000
5	.13	11.0	201,000
7A	.16	24.6	203,000
7B	.17	36.0	250,000
9	.12	91.5	582,000
10	.11	127.0	984,000
12	.11	220.0	2,670,000

used since reaches were presumably receiving sediment from the entire watershed. One problem with this approach was that scoured pool volume, fine sediment volume and total delivered sediment correlated positively with drainage area while V* was negatively correlated (Figure 26). One factor controlling this is that scoured pool volume tends to increase exponentially with drainage area since both channel width and depth are power functions of drainage area (Figure 28). As discharge increases, pool volume and fine sediment volumes increase as well, independently of sediment supply.

Relationship Between Residual Fine
Sediment Volume and Residual Scoured
Pool Volume

Pistol River, Oregon

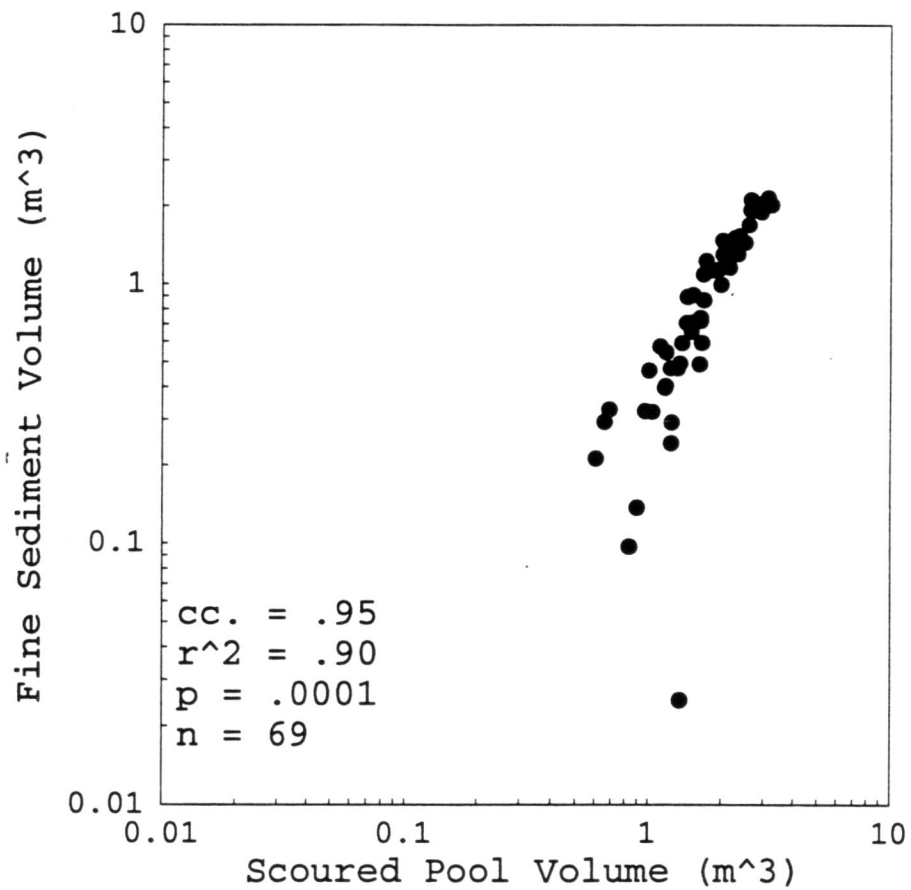


Figure 24: Relationship Between Volume of Fines and Scoured Pool Volume

**Relationship Between V^* and
Residual Scoured Pool Volume**

Pistol River, Oregon

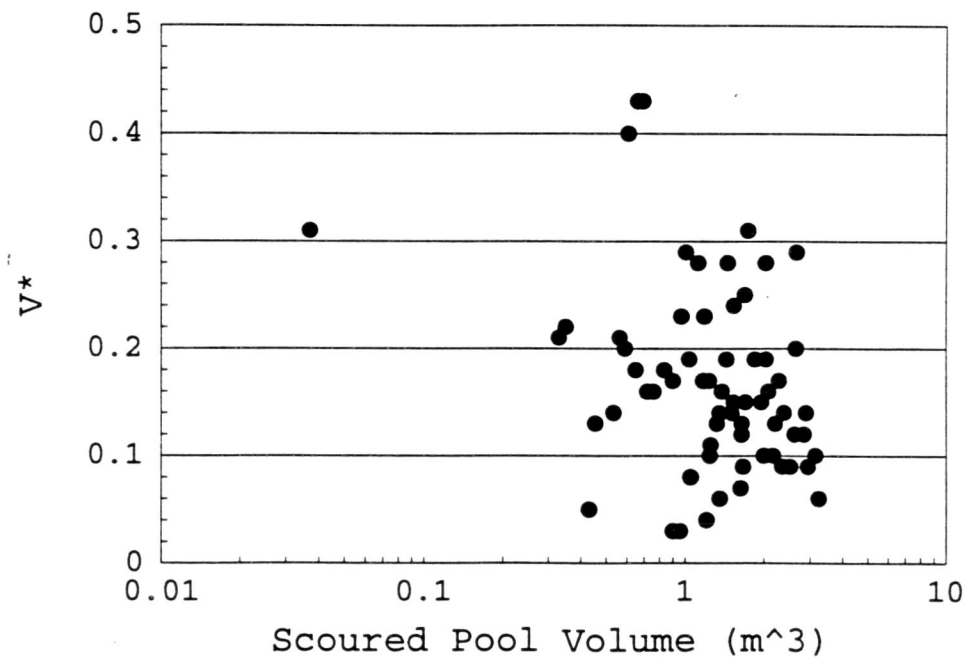


Figure 25: Relationship Between V^* and Scoured Pool Volume

The correlation between total sediment delivery and drainage area further complicates deciphering the relationship between V^* and sediment supply. In order to detrend the drainage area effect, delivered sediment was divided by its drainage area and the normalized data was plotted again (Figure 29). V^* varied positively, but not significantly, with normalized sediment delivery ($r^2=.14$, $p=.4$, $F=.84$).

To further test pool response to sediment delivery, reach 5 was split into 2 reaches, 5A and 5B, at a tributary delivering approximately 45,000 m^3 of sediment (to reach 5b) between 1979 and 1986. V^* above and below this point were calculated along with drainage area. V^* above the sediment input point equalled .07 and V^* below this point equalled .16. When the data was re-analyzed using 5A and 5B, a positive correlation was found ($r^2=.60$, $p=.05$), between V^* and sediment supply (Figure 30). This increase suggested that V^* with proximity to a sediment source. The addition of the divided reaches accounted for much of the variability of V^* . The key lies in the fact that the combined reach 5 had a relatively large sediment supply over a long period of time while reach 5B, alone, experienced a large, recent introduction of sediment. The V^* for reach 5B probably reflects the direct result of recent, large and proximal delivery of sediment from the tributary.

Relationship Between Reach Measurements and Drainage Area

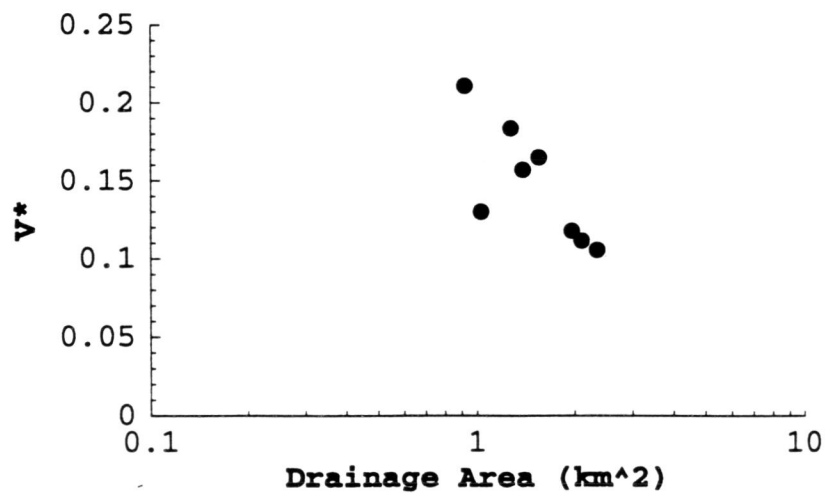
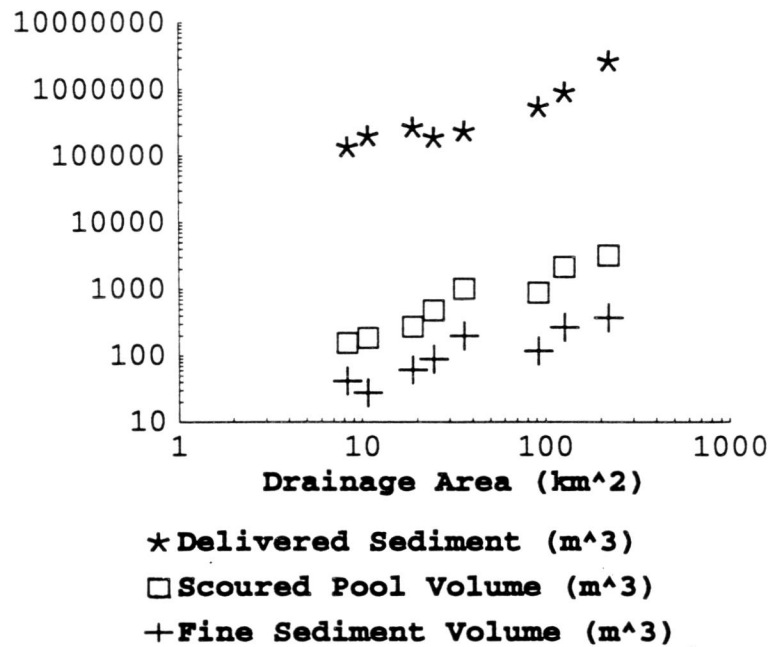
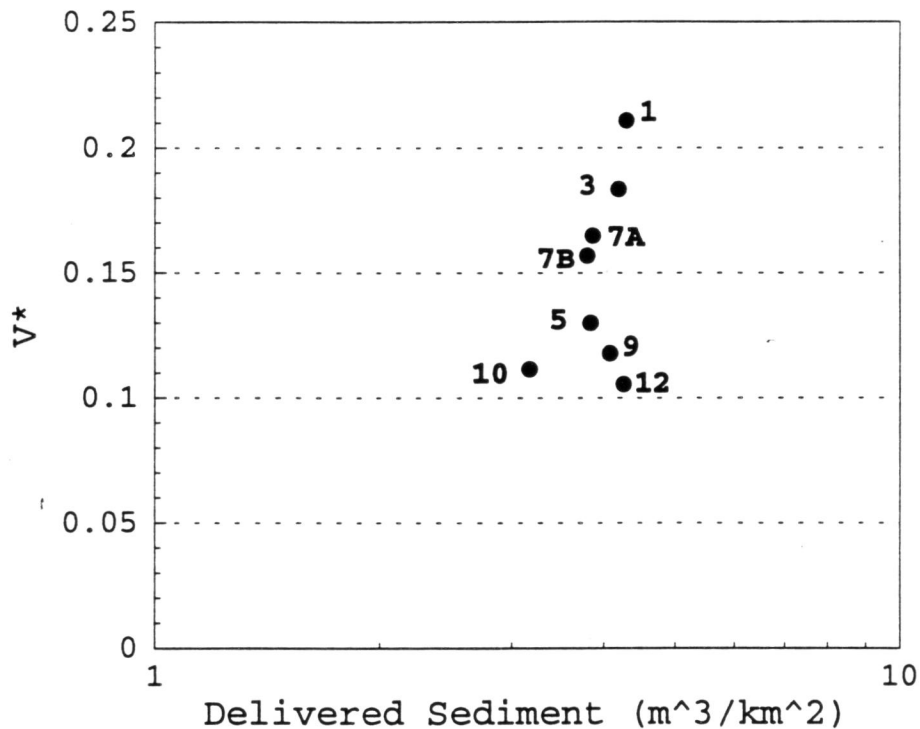


Figure 26: Relationship Between Drainage Area and dependent variables V^* , delivered sediment, residual pool fine sediment and scoured volume.

**Relationship Between V^* and
Sediment Delivery**

Pistol River, Oregon



c.c. = .42

r² = .17

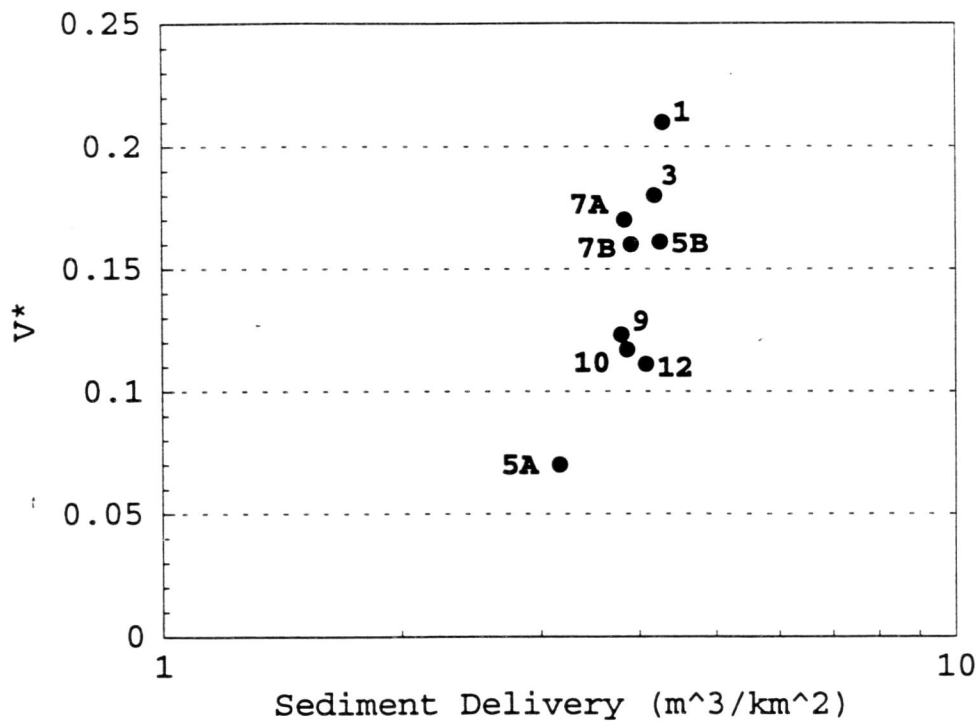
p = .40

n = 8

Figure 27: Relationship Between V^* and Unit Area Sediment Delivery using 8 Study Reaches. Points are labelled with reach numbers.

**Relationship Between V^* and Sediment Delivery
(modified)**

Pistol River, Oregon



c.c. = .78

$r^2 = .61$

p = .01

n = 9

Figure 28: Relationship Between V^* and Unit Area Sediment Delivery using 9 Study Reaches (Reach 5A & 5B). Points are labelled with reach number

The absence of higher pool sediment storage in reach 5A may be explained by the storm in 1964 and very low sediment supply since then.

While delivered sediment strongly correlated with V^* in reaches, the temporal and spatial variation of sediment delivery over the past 50 years also influenced the amount of sediment observed in pools. Even though the assumption was made that all sediment delivered above a reach contributed to that reach, the residence time of sediment and sediment transport distance from source areas are factors that further influence sediment storage. Observation of the landslide sediment delivery data relative to the sample reaches revealed V^* to be sensitive to the proximity of the entry point of sediment to the stream and to the time period in which the sediment was delivered.

To further test the sensitivity of V^* to local sediment input, the landslide inventory map was used to determine the time period and distance from each sediment entry point to the top of each reach to which it contributed. These data provided a measure of the time and distance landslide delivered sediment was transported to influence pool morphology. Cumulative distribution curves were then derived for the number of landslides delivering to each reach by time period and distance from delivery point, and a median point from each curve was taken. A three-dimensional

analysis was conducted using V^* against these derived indices of spatial and temporal pattern of sediment input (Figures 29).

The results of the analysis qualitatively show that in Pistol River, the highest V^* 's correspond with the closest and most recent delivery. The uppermost reach 1 and reach 5A were the only exceptions. Reach 1 received most of its sediment from landslides less than 2000 meters away and prior to 1964. The high V^* can be explained by the presence of a large, active earthflow on the slope approximately 150 meters upstream of the top of the reach. This reach has experienced a slow but constant supply of sediment from landslides and gullies as a result of the earthflow over the past several years. As noted in the sediment production analysis, the earthflow was identified in 1940 aerial photographs. Even though landslides as a result of the earthflow were included, gully erosion was not quantified within specific time periods and the time and distance element for gullies contributing to reach 1 was not included in the distribution curve. Furthermore, rill, sheetwash and additional landslide scarp erosion was not measured. These additional erosional features may be contributing sediment to streams on a regular basis, particularly since these features tend to produce fine-grained sediment. Reach 5A received relatively small sediment delivery quantities, most

of which was delivered prior to 1965. Much of this sediment may have been transported downstream as a result of the storms in 1955 and 1964.

V*, Delivery Distance and Delivery Time

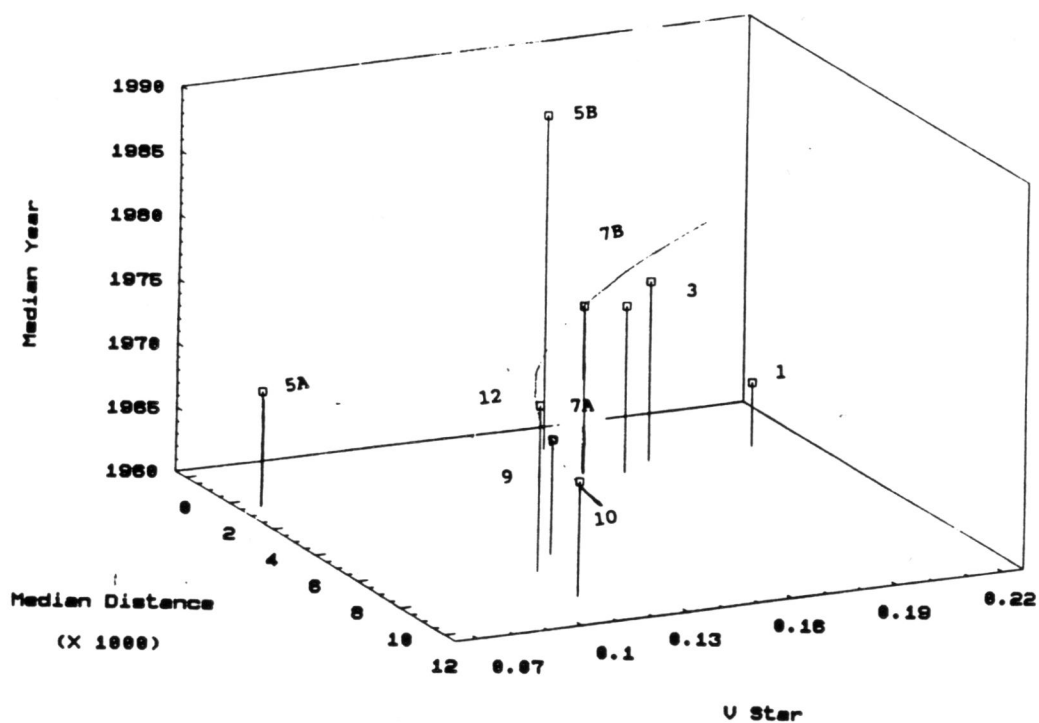


Figure 29: Qualitative Representation of V*, Delivery Distance and Year. Distance and Year represent median values relative to the number of landslides that delivered to a reach.

DISCUSSION

The landslide inventory and hillslope analysis indicated that most sediment was delivered from streamside landslides into upland channels in both forested and managed areas. Rates of landslide sediment delivery were higher on roaded and harvested slopes than on forested slopes, suggesting that management activity accelerated sediment delivery to channels over the natural rate during the 50-year time period. Correlation between sediment supply and fine sediment storage in pools indicated pools were responding to this increase in sediment supply. The addition of time since input and distance to the analysis helped to explain the pool response. Higher V^* corresponded with higher levels of sediment delivered per unit area as well with the most recent and the closest sediment supply. Thus, in Pistol River, V^* reflected local sediment supply. The relationship between fine sediment volume in pools and sediment delivery indicates that landslide sediment delivery from years passed is being transported through the stream system, and then stored in downstream pools, bars, terraces and floodplains. Upstream reaches that had recent sediment supply and higher V^* values were narrow and somewhat constrained by bedrock limiting lateral movement of the stream and terrace and floodplain formation. Upper reaches

were also more complex with more visible boulders and large wood. Overall, narrow, upstream reaches tend to temporarily trap fine sediment due to their complexity. These complex features tend to reduce sediment transport in the short term, as reflected in the relatively higher percentage of fines observed in pools. Therefore, in the short term, fine sediments are stored in pools in upland reaches. Over time, storms and high flows transport sediment downstream to unconstrained reaches where it is stored in a variety of storage locations, including pools. While reaches in the lower part of Pistol River had some fine sediment in pools, much of the sediment was stored in bars. Even though unconstrained, downstream reaches had relatively high sediment supply over time, this was not seen in the V^* values because sediment deposition was not confined to pools and because sediment input was not local. The analysis suggests that the lower reaches are storing older sediment in several locations, while the upper reaches are storing newer, or recent sediment, primarily in pools.

Hillslope analysis indicated overall sediment production and delivery is declining in Pistol River, although this may be misleading due to the absence of a major storm since 1964. Because older road construction and harvest units continue to produce landslides, these areas are more vulnerable to the next big storm unless efforts are

made to stabilize slopes. Recent methods of road construction, riparian management plans and harvest practices may, however, reduce the effects of a big storm event.

As for fish, sediment in pools is only one variable that can adversely affect habitat. Temperature, dissolved oxygen and turbidity are also problems associated with timber harvest and road construction. Accelerated sediment delivery to channels, as well as many other problems, can be minimized by leaving effective buffers along all streams, whether they are fish-bearing or not. Currently, the situation in Pistol River is somewhat questionable. The lack of major storms for the past 30 years suggests that the landscape could be vulnerable to a period of increased sediment production and delivery. Although new and improved forest practices have been in place for several years, the effectiveness of these new methods in Pistol River have not been fully tested yet.

V* as an Indicator of Mobile Sediment in Channels

Overall, V* proved to be a useful tool in detecting pool response to sediment supply but on a local level. One would expect to find low V* values in a sediment limited channel and high V*'s in a sediment rich channel. In Pistol River, the lowest V*'s were found in channels with an

abundance of bar stored sediment. Local sediment input may be masking basin trends in sediment supply to pools. Accounting for total sediment storage within the channel in addition to pools would clarify the role of local versus basin-wide supply.

Lisle and Hilton (1992) discussed limitations of using V^* , such as basin geology that does not produce fines, sample pool complexity, pool sample size and working with relatively large river systems. Other limitations may be in using V^* for evaluating basin level effects of sediment delivery to channels.

SUMMARY AND CONCLUSIONS

Sediment Production and Delivery

Landslides are responsible for the majority of sediment production in Pistol River, although earthflows and gullies in the upper watersheds also contributed sediment. Primary factors influencing landslides are unstable geology, inner-gorge steep slopes and management activity. Management activity such as road construction and harvest increased the rate of landsliding over forested areas by a factor of 32 and 2.8, respectively.

Sediment production from landsliding has increased as management has increased, while production from forested areas have decreased over this same time period. Overall, total sediment production has declined since 1955. Rates of sediment production are generally over 600 times greater on privately owned land than Forest Service and BLM land, however, BLM had the greatest slide rate on harvested slopes. BLM's harvested rate was over 300 times the forested rate, suggesting land use influenced landsliding. Much of the BLM and privately owned land is in moderate to high hazard zones for landslides.

Of the sediment produced on hillslopes from landslides, 86% was delivered to Pistol River streams at a rate of $400\text{m}^3/\text{km}^2\cdot\text{yr}$, and 80% was delivered from managed

lands. Delivery of sediment from landsliding is primarily from streamside debris slides along steep inner-gorge slopes in first to fourth order channels. Management activity accelerated the delivery of sediment delivery by constructing road and conducting harvest in or near steep riparian slopes.

Sediment Storage in Pools and V^*

No relationship was found between V^* and scoured pool volume suggesting that V^* is independent of pool size. Lisle and Hilton (1992) found similar results in that sediment production affected volume of sediment stored in pools and not the volume of storage available in pools. V^* decreased with increasing total sediment delivery in the downstream direction, while fines, scoured volume and sediment delivery increased. Each of these variables correlated highly with drainage area. Detrending the drainage area effect resulted in a positive correlation between sediment delivery and fine sediment storage in pools, but only after the effects of localized sediment input were considered. The positive correlation between delivered sediment and V^* are explained by time and distance of delivery.

A qualitative relationship exists between recent and close sediment delivery and V^* suggesting V^* to be most appropriately used as an indicator of local sediment delivery.

Evaluating fine sediment in pools has the potential to be a useful indicator of local sediment supply. Additionally, V^* used in conjunction with sediment budgets can be used in watershed analysis for assessing historic and current conditions. These tools used for watershed analysis have implications for land managers in interpreting land use effects on channel morphology and fish habitats.

This study and others like it can guide land use decisions by giving managers information concerning hillslope areas vulnerable to mass wasting and surface erosion to minimize adverse affects on aquatic environments. The concepts developed by Dietrich (1982,1989) and Lisle and Hilton (1992) and others must be further researched to develop more refined uses for V^* . As Dietrich (1982) explains, understanding the links between all the variables and processes is essential in defining or understanding the whole system.

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APPENDIX

DATA DICTIONARY:Landslide Type (from Varnes, TRB Pub 176)

Debris slide	DS
Debris avalanche	DA
Debris flow (within stream channel)	DF
Simple slump	SS
Slump-earthflow	SE
Rock slide	RS
Surface ravel	SR
Gully erosion	GE

Geomorphic Position (may add more entries to dictionary in future)

Streamside slide	S
Toe of deep-seated slide form	T
Head scarp of deep-seated slide form	H
Lateral margin of deep-seated slide form	L

Photo-interpreted Activity Level

Active	A
Past Active	P
Landslide Form	F

Field-verified Activity Level

Active	1
Subactive	2
Possibly Active	3
Dormant	4

General site code

Road-related	R
Harvest-related	H
Road and harvest-related	M
Naturally occurring	N
Wildfire-related	W

Slope Position

Concave	
Convex	CV
Planar	CX P

Verified?

Photo-Interpreted	PI
Stereoplotter-Measured	SM
Field-Measured	FM

LANDSLIDE INVENTORY DATABASE INPUT FORM

LOCATION

National Forest Watershed/Forest Subwatershed/
Geotech Point Data Number: _____ Township/Range/Section: _____

PHOTO-INTERPRETED INVENTORY

Landslide Type: _ DS DA DF SS SE RS SR GE
 Geomorphic Position: _ S T H L A P slope position: CV CX P
 Activity Level: _ A P F
 General Site Code: _ R H M N W

Initiation Date: oldest _____ youngest _____ photo/yr: _____

FIELD-VERIFIED INVENTORY

Activity Level: _ 1 2 3 4 Field Observation Date: _____

SITE DATA (if any)

Road Construction

Timber Harvest

Road Number: _____

Unit Name/Number: _____

Date: _____

Date: _____

MEASUREMENTS

Length (ft): _____ Width (ft): _____

Depth (ft): _____ Area (sq ft): _____ Volume (cubic feet): _____

Percent delivery to channel: _____ Percent of delivery LWD: _____

Continued as debris flow? (Y or N): _____ Channel length affected (ft): _____

Verified?: _ PI SM FM

