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LONG-TERM PATTERNS OF WATER QUALITY IN A MANAGED WATERSHED IN OREGON: 1. SUSPENDED SEDIMENT[1]

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ABSTRACT: The cumulative effects of forest management activities on water quality at a downstream point were monitored from 1972-1980 during development of a watershed for timber resources. Suspended sediment concentration and turbidity were measured at two hydrologic stations which bracketed a 10-km reach of the Middle Santiam River in the Western Cascades of Oregon as it flowed through an 8000-ha block of intensively managed forest land. Slope failures often accompany road building and harvesting in steep forested watersheds and pose the most serious threat to water quality. Although 180 km of road were constructed and 3400 ha of old-growth forests were harvested from slopes averaging over 60 percent, long-term changes in sediment yields remained undetectable during the period of measurement. The geologic characteristics of the basin and the road construction and maintenance techniques as prescribed by Oregon's forest practice regulations helped to minimize the occurrence of slope failures so that long-term changes in suspended sediment export rates did not occur. Throughout the nine-year measurement period, seven slope failures which added sediment directly to streams produced measurable short-term responses at the downstream sampling location, but these erosion events were too small and too infrequent to produce long-term changes in sediment yield from the watershed.
(KEY TERMS: water quality; forest management; suspended sediments; cumulative effects.)

INTRODUCTION

While forest management has been shown to affect water quality in headwater streams, little information is available on the possible effects in downstream reaches as numerous small channels converge to form larger and increasingly integrated stream systems. The so-called "cumulative" effects of forest management activities on water quality through time or at downstream points in the watershed is a land management issue of growing concern in the Pacific Northwest region where a large area of forest land is intensively managed for both timber and water resources.

Managing a watershed for commercial forestry requires construction and maintenance of a road network and regular entry into the forest stands for various silvicultural activities including harvesting, planting and thinning. Silvicultural activities are conducted on small units of land area and are spaced 5 to 15 years apart during lengthy crop rotations. Many studies of small forested watersheds in the Pacific Northwest and elsewhere have shown that disturbances of the forest may cause a significant increase in sediment export (Fredriksen, 1970; Brown and Krygier, 1971; Swanston and Swanson, 1976; Beschta, 1978; and many others). Most of the increase in sedimentation associated with forestry activities is attributed to forest roads (Fredriksen, 1970). Poorly located or inadequately constructed roads can add to erosion by increasing the frequency of mass failures on steep slopes (Dyrness, 1967; Swanston and Swanson, 1976). Sediments washed from ditches and gravel road surfaces during storms are a smaller but more chronic erosion product in managed basins (Reid, 1981). While it appears that improved forest management techniques such as those included in Oregon's forest practice operating guidelines can reduce erosion response in harvested basins (Beschta, 1978; Fredriksen and Harr, 1979; McCashion and Rice, 1983), the concern remains that progressive development of forest drainage basins may lead to cumulative sedimentation impacts on stream resources that occur in either time or space (Swanson and Fredriksen, 1982; Geppert, *et al.*, 1983).

The complex patterns in which water and erosion products are routed through the stream network may limit our ability to apply the knowledge gained in small forested watershed studies to predict the response of larger watersheds. Wolman (1977) noted that little is known about the sequential processes involved in the systems of erosion and transportation as sediments move from source through channel systems, with intermittent periods of storage. Dietrich, *et al.* (1982), stressed that no transport process is sufficiently well understood to predict transport rates in forested stream systems.

The purpose of this study was to measure the integrated effects of timber harvesting and road construction on the export of suspended sediments from a medium-sized watershed in western Oregon through time. The water quality data covered nine years of commercial development of 8000 ha of forest land for timber resources, including the construction of an extensive road network and the conversion of a large area of old-growth forest to plantations.

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STUDY AREA

Physical Features

The study area included 8000 ha of the Middle Fork of the Santiam River watershed located on the western slopes of the Cascade Range in Oregon. The Middle Santiam River flows westward from the crest of the Cascade Range to Green Peter Reservoir 30 km downstream, encompassing a total watershed area of approximately 28000 ha. Water quality was monitored at river sampling stations 1.5 and 11.0 km upstream from the reservoir as the river flowed through a large block of commercially-owned forest land in the middle of the basin; the area above these two stations is 28344 ha and 20262 ha, respectively. The portion of the watershed that lies between the two sampling locations forms the study area whose boundaries are shown in Figure 1. The watershed rises in elevation from 335 m at the lowermost reach of the river to 1465 m at the top of the east-west trending ridges that contain it.

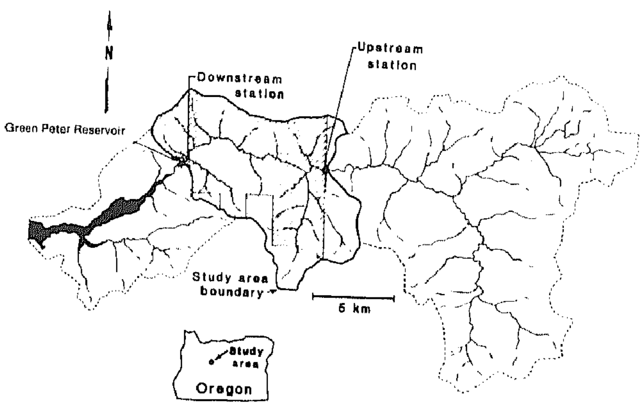

Figure 1. Middle Santiam River Study Area. The shaded portion is the area managed during the nine-year study period.

The main river flows through a straight river valley forming steep, convex slopes in the study area. Some of the channel is carved into bedrock and a floodplain was absent along the entire reach of the river, although a discontinuous terrace occurred about 3 m above the active channel at several points along the river. The Middle Santiam River within the study reach was a fifth order stream with a gradient of 1.2 percent. The channel was mainly a series of rapids and boulder fields of coarse alluvium without regular meandering pool and riffle sequences. Extensive deposits of fine sediments did not occur along the study reach, although fine deposits could be found along the river's banks and in deep pools.

Underlying bedrock of nearly the entire study area consists of andesite flows with tuff breccia of Miocene age, mapped by Peck, *et al.* (1964), as the Sardine formation. Dyrness (1967) reported that slopes develped on the andesite rocks of the Sardine formation are moderately stable, although he noted that slopes greater than 60 percent are susceptible to shallow debris avalanches. Massive unstratified deposits of large, angular boulders in some of the narrow valley bottoms of the study area provided evidence that debris avalanches and slump earthflows have occurred historically. Ridges are capped by a volcanic platform of mixed basaltic andesite lava flows which form stable slopes. Although not represented in the study area, approximately 30 percent of the headwaters portion of the watershed upstream of the upper sampling site is underlain by the Little Butte formation of Oligocene-Miocene age which is described by Peck, *et al.* (1964), as basalt and andesite flows interbedded with volcaniclastics. Slopes developed on the Little Butte formation are highly susceptible to mass failures, many of which have earthflow characteristics and are large in volume (Dyrness, 1967; Fredriksen and Harr, 1979; Hicks, 1982).

The hillslopes of the study area average over 60 percent gradient and are strongly dissected with deeply incised stream channels. Slopes in excess of 60 percent occurred on 58 percent of the area. The soils found on these slopes are shallow to moderately deep and medium textured, developing from a mixture of andesite, rock colluvium and volcanic ash from nearby Cascade volcanoes of Quaternary age. Fine-textured colluvial soils occur on moderate and gentle slopes and in depressions. These soils have well-drained clay loam topsoils overlying friable clay loam subsoils (Duncan and Steinbrenner, 1973).

The climate of the region is marine with cool, wet winters and warm, dry summers. Most of the precipitation falls as rain between October and April and results from long-duration, low-intensity frontal storms. The largest floods generally result when snowmelt accompanies storm rainfall (Harr, 1981). Snow accumulates to depths of 1-3 m at elevations above 1100 m. Annual precipitation ranges from 1500 mm at the lower elevations to 3300 mm at the higher elevations reflecting the strong orographic effect produced by the Cascade Mountains. A rain gage located since 1972 at 370 m elevation within the study area recorded an average of 2200 mm of precipitation annually.

Overstory vegetation on forested slopes was predominantly 350-year old Douglas-fir (*Pseudotsuga menziesii*). Ridgetops had a mixture of western hemlock (*Tsuga heterophylla*), pacific silver fir (*Abies amabilis*), and subalpine fir (*Abies lasiocarpa*). Alluvial valley bottoms and undrained depressions supported mixed stands of bigleaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*) and western red cedar (*Thuja plicata*).

Management Practices

Road construction and timber harvesting of old growth forests began in 1972 in the industrially-owned block (5270 ha) shown as the shaded area in Figure 1. This block has been owned and managed by the Weyerhaeuser Company since 1923, and constitutes 72 percent of the portion of the watershed under study. The forest lands in the Santiam vatershed upstream of the study area have been administered ɔrincipally by the Willamette National Forest. Activities vere conducted according to rules prescribed by the Oregon 'orest practice regulations that were introduced in 1972 to ɪncourage best management practices for forest management ɔn state and private lands. The steepness of the terrain in he study area required care in planning and conduct of ɔperations to minimize land management effects on water ɥuality.

Some timber harvesting in the study area had already oc-ːurred on U.S. Forest Service and other privately-owned ands in the two decades before water quality monitoring ɔegan. Prior to 1971, approximately 15 percent of the study ɪrea had been harvested by tractor and roaded. These areas vere primarily located along the ridge forming the southern ɔoundary of the watershed (Figure 2), and roads and clear-ːuts were located where local topography formed gently sloping basins just below ridgetops. No evidence was found of significant past erosion events in these areas. In addition, approximately 9 percent of the watershed above the upstream station had been logged during the 1950's and 1960's prior to the study; another 5.7 percent of this upper watershed was logged during the study period (Table 1).

The mainline haul road was heavily ballasted and the surface over the drivable width of 8-10 m was surfaced with crushed rock. Surface runoff drained directly to the river or to major tributaries at many points. Most of the roads in the study area were all-weather secondary roads of 4-6 m drivable width with crowned rock surfaces of moderate depth and drainage structures designed to handle the 25-year storm. (Culverts were designed to accommodate the 50-year storm where roads crossed steep draws.) Secondary roads were constructed following contours and using balanced cut and fill design. The gradient of most sideslope roads ranged

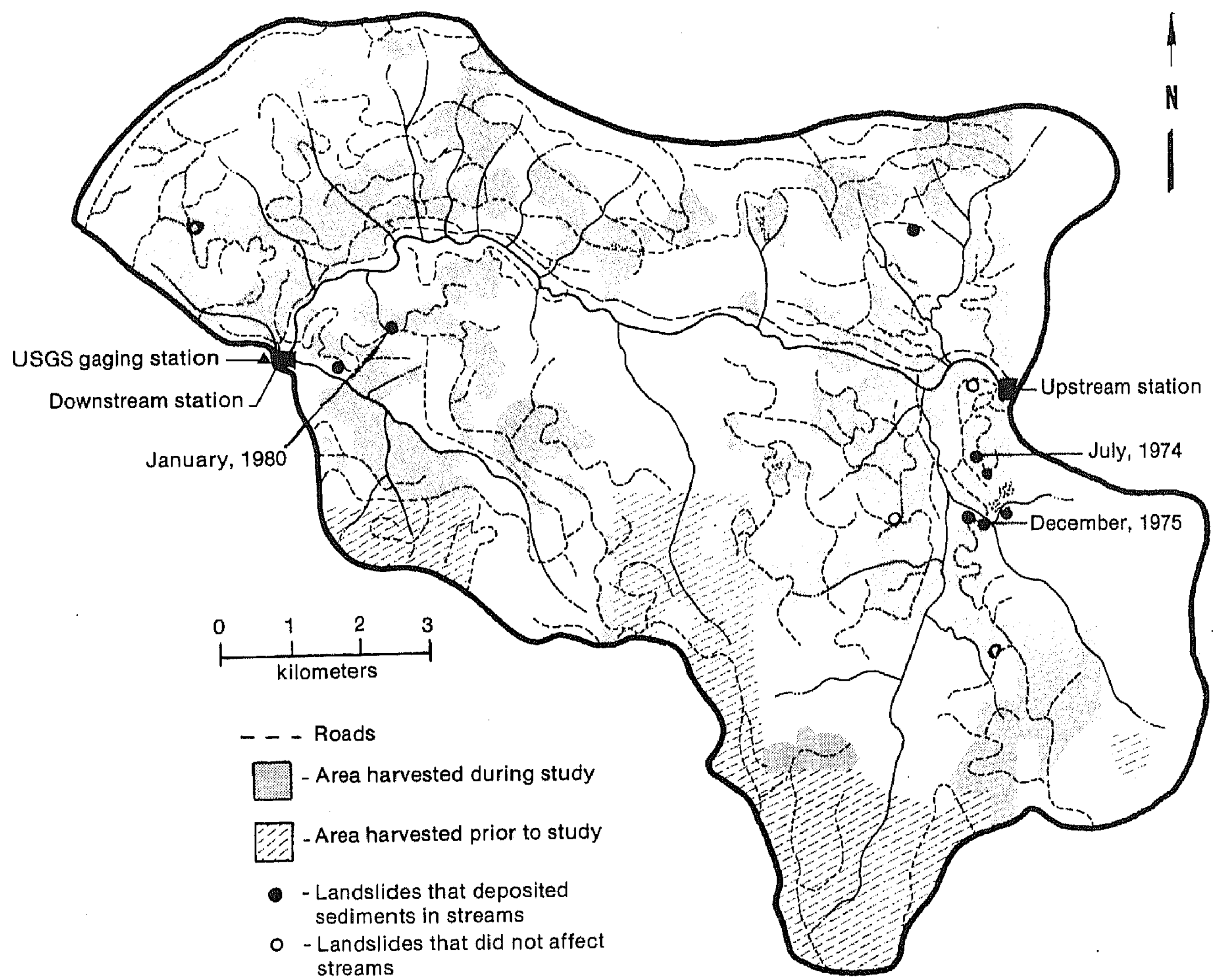

Figure 2. Roads and Harvested Units in the Study Area as of 1980. Landslides are also shown with closed circles representing failures that deposited sediments directly into streams and open circles representing landslides that did not affect streams. The cross-hatched areas were harvested prior to 1967.

TABLE 1. Harvesting, Road Construction and Slashburning in the Middle Santiam Watershed.

Year	Road Construction[a] (km)	Road Use (loads/day)	Harvested: Study Area – Area[b] (ha)	Harvested: Study Area – Portion[c] (percent)	Harvested: Upstream Portion Watershed – Area (ha)	Harvested: Upstream Portion Watershed – Portion[d] (percent)	Burned: Study Area – Area (ha)	Burned: Study Area – Portion (percent)
Prior to 1971	17.6		12.00	15.0	1750	8.8	0	0
1971	0		43	0.5	62	0.3	0	0
1972	7.4	11	107	1.4	81	0.4	0	0
1973	13.8	13	103	1.3	68	0.3	0	0
1974	19.1	27	187	2.4	94	0.5	0	0
1975	32.2	65	352	4.4	210	1.1	96	1.2
1976	21.7	80	403	5.0	34	0.2	150	1.9
1977	20.9	60	305	3.8	0	0	102	1.3
1978	17.7	53	288	3.6	162	0.8	122	1.5
1979	9.9	56	191	2.4	392	2.0	224[e]	2.8
1980	19.2	53	270	3.4	18	0.1	363[f]	4.5
TOTAL	179.5		3449	42.7	2871	14.3	1057	13.1

(a) Includes road construction in study area only.
(b) Includes road right-of-way clearing and U.S.F.S. ownership in the Bear Creek subdrainage.
(c) Based on total study area of 8080 ha.
(d) Based on the area of the watershed lying above the upstream station (20,262 ha).
(e) Includes 133 ha burned by wildfire.
(f) Includes 192 ha burned by wildfire.

between 5 and 12 percent, although a few roads had gradients as steep as 18 percent. Care was taken to avoid locating roads on unstable soils and areas with local concentrations of subsurface drainage. On sites with slopes greater than 60 percent that the engineer judged to be prone to soil slippage, spoils were hauled by truck to stable areas for disposal. A roadgrader operated continually in the study area, providing frequent maintenance of actively used roads and annual maintenance of idle roads. A backhoe cleared culvert inlets twice annually.

Logging of old-growth Douglas-fir was accomplished almost exclusively with highlead cable systems which lifted logs uphill to midslope or ridgetop landings. The few gently sloping sites such as the benches above the valley bottom were logged with tractors. Trees were harvested in units averaging about 20 ha in area, although as cutting progressed, area of contiguous plantation increased. Clearcut units generally were handplanted with Douglas-fir seedlings within one year following harvesting so that clearcut sites were rapidly covered with plantations of conifer seedlings and a vegetative cover protected soils almost continually.

METHODS

Water samples were collected from two locations in the mainstem of the Middle Santiam River. The upstream station was located where the river enters the study area from the east and the downstream station was located 11.1 km downstream (Figure 1). Since 1963, stream discharge has been measured at the U.S.G.S. gaging station located within 30 meters of the downstream station. Flood frequency analysis of annual peak flows from 1963 to 1980 was based on a Log Pearson Type III distribution (Benson, 1968). Precipitation was monitored continuously with a tipping bucket rain gage at a weather station located near the downstream sampling location.

Water samples were collected every six hours from October 1971 through October 1980 with an automatic pumping sampler, Instrument Specialties Company Model 1680 (ISCO). Some error in sediment estimation probably occurs in using a regular, although frequent, sampling interval. Beschta (1978) discussed seasonal and storm-related variability in sediment concentration/discharge relationships, noting the importance of sampling more intensively during storm events in determining the effects of land management on sediment export. The duration of stormflow was often several days or longer, ensuring that samples were taken several times during most storms. Sediment samples were collected during 23 of the 27 floods with peak flows greater than 127 m^3s^{-1} (U.S.G.S. base storm flow) recorded during the nine-year interval.

Water samples were returned to the lab weekly for analysis. Samples were analyzed gravimetrically for suspended sediment concentration (SSC expressed in mg L^{-1}), following the methods of Guy (1969). Turbidity was measured using a Hach 2100A Nephelometer; results are expressed in nephelometric turbidity units (ntu). A good relationship was found between the common logarithms of turbidity and suspended sediment at both sampling stations (r^2=0.67 and

During the study there were times when data were when equipment malfunctioned or the hydrologic sta- were inaccessible. Sediment concentrations for those were estimated from regression curves relating log sedi- concentration to log discharge (r^2=0.35). Sediment were lost from both sites 6 percent of the time during ine-year study.

ıe upstream sampling site was located where the river between bedrock banks and lies just upstream from a flattening of the channel gradient. The U.S.G.S. placed ond gaging station at this site in August 1980. The d channel at winter baseflow was about 20 m wide at point, and the substrate varied from gravel to cobble in The sampler intake was attached to a bedrock outcrop ıding into the main flow at about one-fourth flow ı and one-fourth channel width at storm flows. Flow swift at the intake point, but turbulence did not break urface. The downstream sampling site was located at nd of a local steepening of channel gradient. The chan- ıas about 25 m wide and large boulders were distributed ıghout the reach, forming rapids at high flow. Although sampler intake was placed in a small pool behind a ler and was separated from the main current by about neter, considerable turbulence kept sediments suspended. intake of the sampler was attached to a rod embedded e channel approximately 0.3 m from the channel bottom ıt about one-fourth channel width at high flows.

diment yield per unit area was estimated by multiplying average daily sediment concentration by daily discharge dividing by watershed area. Annual or season sediment was computed by accumulating daily yield estimates. ıal discharge-weighted suspended sediment concentration ach of the stations was determined by dividing total an- sediment yield by total annual flow. Sediment yield he study area was computed by subtracting the upper rshed sediment yield from the total watershed yield ıated at the downstream station. Daily flow at the up- m station was estimated by comparing daily flow at the U.S.G.S. gaging stations during the 1981 hydrologic when both stations were operative. Flow at the up- m station was 69 percent of that at the downstream on on the average (weighted by discharge), although the varied from 59 percent during the summer to 84 per- during snowmelt. The discharge-weighted average was ied for all seasons, since nearly all sediment was trans- ed when this ratio provided the best estimate of the re- nship between the stations. Applying a seasonally vary- atio had a negligible effect on sediment yield estimates.

urbidity relationships between the stations were com- d using paired values to estimate treatment effects within managed block. The difference in turbidity between ologic stations was computed by subtracting upstream idity values from their paired downstream values so that difference variable reflects the differences in water ity as the river flowed through the study area. A positive ıber means that the downstream value was greater than its paired upstream value, indicating that turbidity increased in the study reach. Although the value of the difference variable might be positive or negative on any given day due to random variation, an average value of zero was expected if the erosion rates were the same for the two portions of the watershed.

The effect of timber harvest and road construction on sediment export from the study area can be assessed by comparing the difference in values of parameters measured at the upstream and downstream stations. The upstream station provided a relatively unmanaged watershed against which the effects of land management activities on water quality within the 8000 ha study area could be compared. Because there was no experimentally controlled grouping of data such as pre- and post-treatment or paired watersheds, the significance of watershed treatment on sediment yield and water quality through time is best illustrated by graphical presentation of the data.

RESULTS

Precipitation and maximum and mean discharge per square kilometer of watershed above the downstream station by hydrologic year are listed in Table 2. Several moderate floods occurred during the study, including 15- and 10-year floods as well as six peak flows with approximately two-year return intervals (Figure 3). The largest flood of the study period (return interval of 15 years) was recorded in January 1972, soon after the study began and before much logging or road construction had occurred. The largest flood measured at the Middle Santiam gaging station in the 17 years of record occurred in December 1964 and had a return interval of approximately 100 years and a discharge of 648 m^3s^{-1}.

The estimated annual yield of suspended sediment for the upstream and logged portions of the watershed are shown in Figure 4. Sediment yield was greatest in 1972 coincident with the 15-year flood and smallest during the 1977 drought. Average sediment yield was 126 metric tons km^2 yr^{-1} for the study area and 160 metric tons km^2 yr^{-1} for the watershed above the upstream station. Higher sediment yields from the headwaters of the watershed probably reflect the more erosive and unstable soils in that portion of the basin (Hicks, 1982), although slopes in the study area were generally steeper than those in the upper portions of the watershed. These yield values for portions of the Middle Santiam basin were in agreement with other reported values of suspended sediment yield from the region (Anderson, 1954; Larson and Sidle, 1980; Patric, *et al.*, 1984), although direct comparison of these estimates to other yield estimates was difficult because of differences in watershed areas, lithologies, climatic conditions or land use.

Most of the suspended sediment load was transported during a few large storm events, although small amounts of sediment were carried by the river throughout the year. Only suspended sediment concentration and turbidity averaged monthly are shown in Figure 5. The estimates of maximum

TABLE 2. Climatic and Streamflow Characteristics for the Study Area and Discharge-Weighted Suspended Concentrations for Each Portion of the Watershed by Hydrologic Year (October 1-September 30).

Year	Precipitation (mm)	Discharge Per Unit Area ($m^3s^{-1}km^{-2}$)			Suspended Sediment Concentration (mgL^{-1})	
		Maximum	Minimum	Mean	Upper Watershed	Study Area
1972	2950	1.47	0.0041	0.09	174	104
1973	1586	0.59	0.0042	0.04	38	32
1974	2887	0.92	0.0038	0.10	61	24
1975	2284	0.91	0.0029	0.07	61	41
1976	2650	0.87	0.0054	0.08	46	75
1977	1543	0.15	0.0049	0.03	6	5
1978	2608	1.36	0.0068	0.07	99	81
1979	2068	0.70	0.0042	0.05	71	39
1980	1966	0.63	0.0037	0.07	80	– –
Mean	2282 (SE=176)	0.84 (SE=0.13)	0.0044 (SE=0.00038)	0.07 (SE=0.008)	71 (SE=16)	50 (SE=15)

instantaneous suspended sediment concentrations measured during the study were 1700 mg L^{-1} at the upstream station and 1000 mg L^{-1} at the downstream station, which occurred during the large flood in 1972. Sediment rating curves relating instantaneous values of the log of sediment concentration to the log of stream discharge showed wide variation at both sites (r^2=0.35).

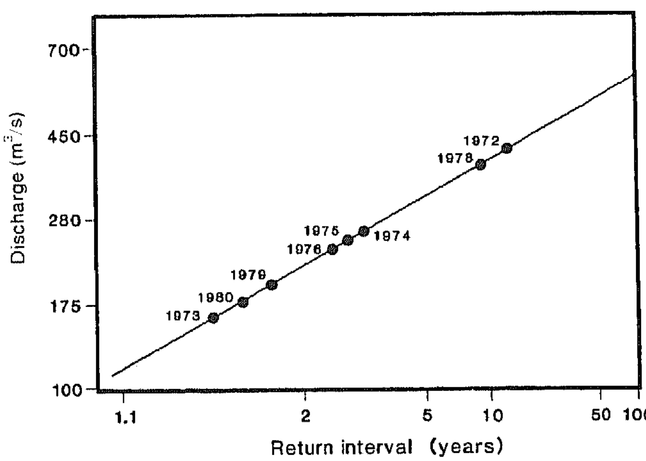

Figure 3. Flood Frequency Analysis of Flow in the Middle Santiam River Near Cascadia, Oregon. Analysis of annual peak flows greater than 127 $m^3 s^{-1}$ from 1963 to 1980 based on a Log Pearson Type III distribution. Plotted points are floods occurring during the monitoring period from 1972 to 1980.

The average annual discharge-weighted sediment concentration at the downstream station was less than the concentration at the upstream station in all years except 1976, indicating that the export rate of sediment per unit volume of discharge and presumably per unit area of the study area wa somewhat less than that for the watershed above the upstrean station (Table 2). That sediment concentration and turbidit tend to be greater at the upstream station suggests that lower erosion rate and dilution by water inflow is implied fo the studied watershed reach.

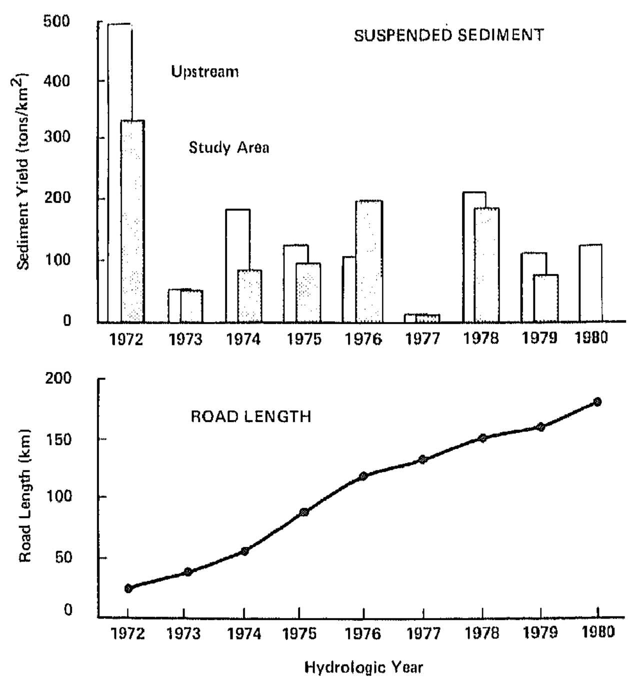

Figure 4. Annual Yield of Suspended Sediment from the Study Area and the Portion of the Watershed Above the Upstream Sampling Location in Metric Tons km^{-2}. The cumulative amount of road constructed in the study area is also shown.

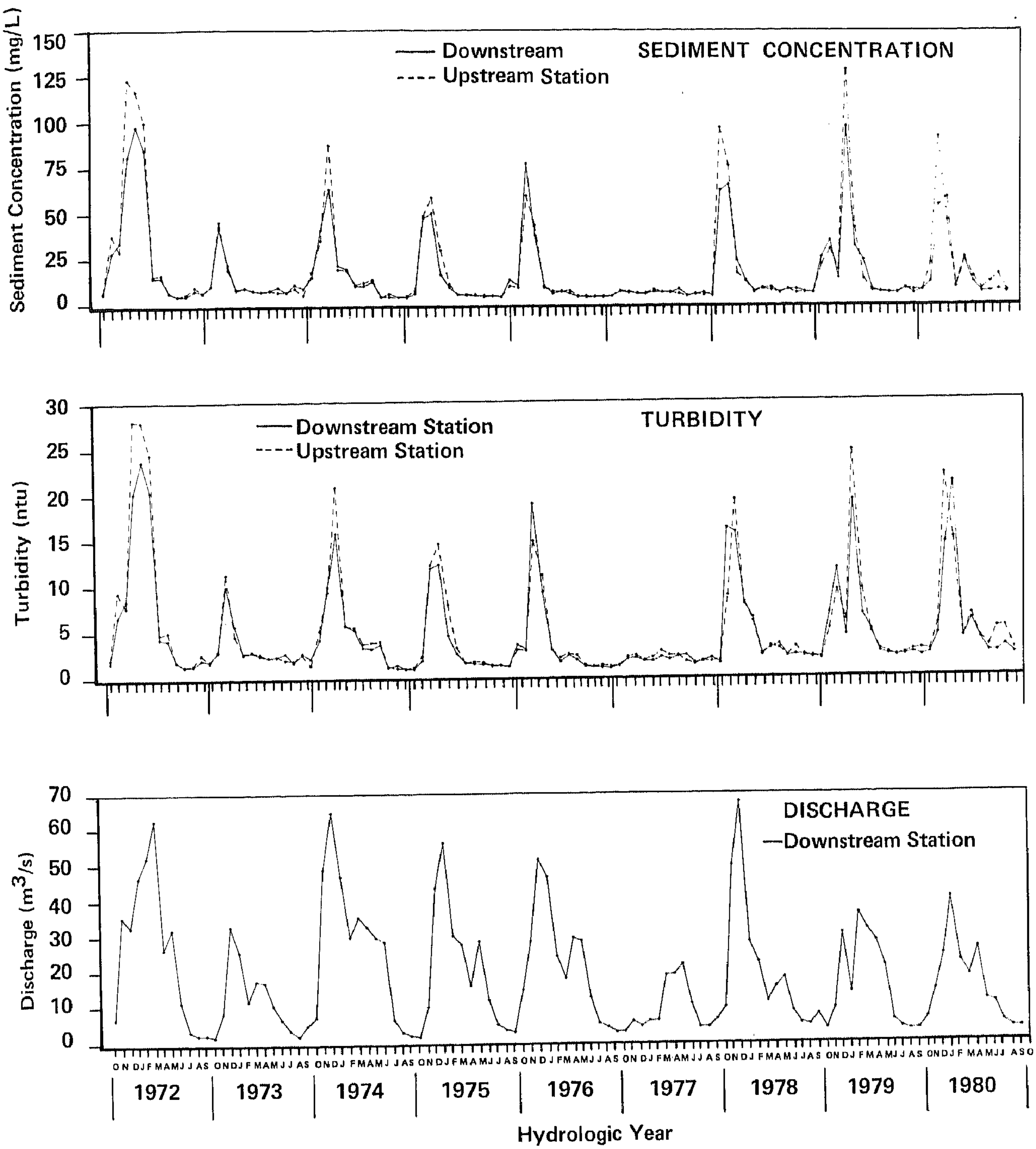

Figure 5. Average Monthly Discharge at the Downstream Station and Average Monthly Suspended Sediment Concentration and Turbidity at Both the Up and Downstream Sampling Stations.

Sediment concentration at the upstream station appeared to increase in 1980, which was a relatively low rainfall year. Hicks (1982) reported that movement of a large earthflow encroaching on the channel of the Middle Santiam River 8 km upstream from the upper sampling station reactivated in November 1979, adding additional sediment directly to the channel more or less continually during rainfall. Daily sediment concentration records show that upstream sediment concentration was especially high during the largest storm of the 1980 hydrologic year and remained above average for the year, apparently resulting in net storage of sediment in the study area that year. The earthflow probably accounted for high sediment concentration at the upstream station and the apparently negative export of sediment from the study area in hydrologic year 1980 (Table 2 and Figure 4). (A negative estimate of sediment yield from the study area could occur if the estimate of sediment load per unit volume of streamflow was greater at the upstream station than at the downstream station.)

The frequency distribution of the turbidity difference variable is shown in Figure 6. As expected, most values are near zero although the mean of the sample is –0.4 ntu (±0.1 SE). Large negative turbidity differences tended to occur during stormflow and were especially prevalent in 1980. Large positive differences usually occurred during the fall and winter months, but they were occasionally measured during spring and summer. Although the probability of occurrence of a positive turbidity difference greater than 1 ntu was approximately 9 percent on any given day (Figure 6), the probability of measuring the same difference on the first day of a storm was significantly greater at 40 percent. The turbidity difference averaged monthly is shown in Figure 7.

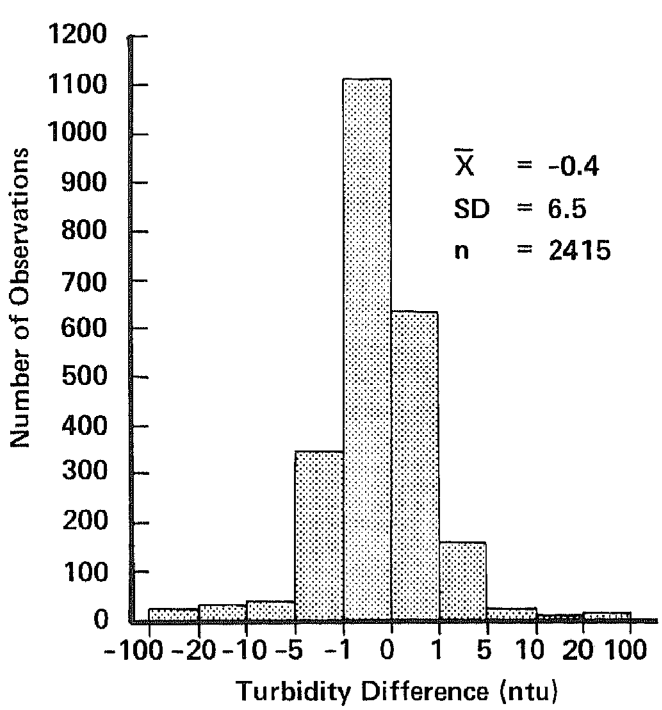

Figure 6. Difference in Turbidity Measured Between Stations Computed by Subtracting Daily Values of Upstream Turbidity (ntu) from Its Paired Downstream Turbidity Value. A positive number indicates that turbidity increased in the study reach of the river. An average value of zero was expected if erosion rates were similar for the two portions of the watershed.

The effects on sediment concentration of erosion processes resulting from forestry activities could be detected in the river between the stations on a few occasions during the nine-year monitoring period. The most significant sediment increases at the downstream station were detected in response to mass failures in the watershed. Twelve mass failures occurred in the study area during the nine-year period, ten of which originated from forest roads. One small landslide occurred in a harvested unit, apparently unassociated with road construction and one mass failure was discovered on a forested hillslope during clearing of a road right-of-way. Landslide locations in the watershed are shown in Figure 2. Most of the landslides were shallow debris avalanches less than 600 metric tons in size (400 m^3), assuming 1.5 tons m^{-3} soil weight; the two largest slides were 3750 and 7500 tons (2500 and 5000 m^3). Seven landslides produced approximately 13,500 tons of sediment over the nine-year period, which were delivered directly to the river and its tributaries. The other five landslides did not directly affect streams.

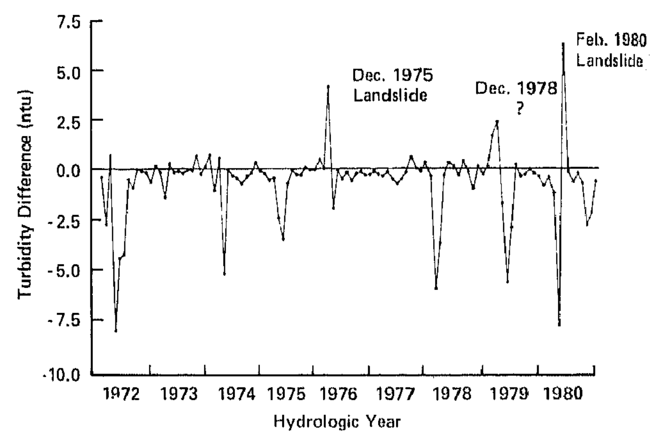

Figure 7. The Turbidity Difference Between Sampling Station (downstream-upstream turbidity) Plotted by Month.

It is not known when the landslide in the forest occurred, but of the eleven other landslides, only four occurred during major winter storms. Stormflow on days when these four landslides occurred was compared to a partial duration series of all floods greater than a baseflow of 127 m^3 s^{-1} during the study period. The one landslide that occurred in a harvested unit unrelated to the road system occurred during the third largest flood of the period, which had a seven-year return interval. The three road-related landslides occurred during storms ranking 7, 11, and 13 of the 27 storm events of the series. Of these, the two large landslides occurred during storms with two-year return intervals. Hydrologic conditions in which these two failures occurred were met or exceeded 14 times during the study period. Six small road-related landslides occurred during minor winter storms and two occurred during summer months.

Sediment concentration at the downstream monitoring station was remarkably sensitive to landslides that occurred even long distances upstream, although one important landslide that occurred just upstream from the station was not detected. Three of the landslides resulted in measurably increased suspended sediment load and turbidity at the downstream station, while three others increased turbidity but did not appear to significantly increase sediment load. The two large positive monthly turbidity differences evident in Figure 7 occurred in response to the two largest mass failures that occurred in the study area. The cause of the smaller increase in December 1978 is not known, although the increase did occur during the first major fall storm after a long drought period. Sediments from mass failures moved as a plume through the system and turbidity response at the downstream station was rapid. Turbidity at the downstream station was usually 1.5-2.0 times greater than upstream turbidity as the sediment plume moved through the system. The duration of increased sediment concentration depended on flow conditions, but usually lasted only one or two days. Some of the sediments from the two larger debris avalanches that were apparently deposited on the streambanks or in channels were entrained during subsequent storms, causing brief periods of higher sediment concentrations up to one month following the original events.

An additional 800 metric tons of suspended sediment, or four times the amount expected, was measured at the downstream station on January 6 and 7, 1975, in response to a road failure 12 km upstream. That failure added approximately 600 tons of road-sidecast sediments as well as some sediment scoured from the channel to the largest tributary to the Middle Santiam River. Although sediment export was clearly higher on these two days, changes in monthly or yearly average turbidity were not detected. A smaller landslide, also of road origin, entered the same tributary in July 1974, causing a small, temporary increase in turbidity, but neither monthly turbidity (Figure 5) nor 1974 sediment yield appeared to be changed by the landslide (Figure 4).

The largest erosion event that could be detected in the water quality data was a mass failure, originating from a road that also entered the channel of the largest tributary to the Middle Santiam River in December 1975 (Figure 2). This landslide added approximately 3700 metric tons (2500 m^3) of soil and road sediments to the stream and resulted in increased turbidity in the tributary at times during the entire hydrologic year of 1976 and in the Middle Santiam River in December 1975 (Figure 5). The sediment from this slope failure may account in part for the greater sediment concentration (Table 2) and larger yield of sediment from the study area in hydrologic year 1976 (Figure 4). Approximately 4000 additional tons of suspended sediment, or 1.4 times the amount expected, was measured at the downstream station over the 11-day period following the slide, while daily sediment yield varied from 1.5 to 10 times the amount expected.

The rapidity with which sediments moved through the system prevented detection of sediment increase following the largest single landslide event that occurred during the study. A landing failed on January 13, 1980, spilling 7500 metric tons (5000 m^3) of sediment directly into the mainstem of the river about 1.5 km upstream of the lower sampling site. Because of the relatively steep channel gradient and high water velocity due to stormflow, a large proportion of the suspendable sediment could have moved past the sampling station within one hour of its entry into the river channel, and was apparently missed during sample collection on the regular six-hour interval. Background turbidity was unusually high during this flood event, further masking the effects of the landslide. However, some sediment from this landslide appeared to move from the watershed during a storm the following month (Figure 7).

SUMMARY AND DISCUSSION

Forest management of the study area was intensive during the nine-year study period. By 1980, 90 percent of the study area had been accessed, yielding a road network 179 km in length with a density of 3.0 km km^{-2} occupying 4.4 percent of the watershed area. Approximately 3449 ha, or 42 percent, of the commercial timber stands had been harvested and replanted.

Results of this study indicate that water quality has remained good during the first decade of commercial development of timber resources in the Middle Santiam River study area. Trends towards increasing sediment yield or turbidity through time were not evident despite incidences of increased sedimentation from mass failures and the growing proportion of the watershed that was roaded and harvested. After nine years of forestry operations in the Middle Santiam basin, long-term detrimental changes in water quality should have been reflected in greater annual yields of sediment at the downstream station and increasingly positive average values of the difference variable. Monthly averages of suspended sediment at both monitoring stations remained within the same range of values recorded throughout the study (Figure 5), implying that sediment export from the upstream portion of the watershed also did not significantly change during the study period, except perhaps in 1980. Sediment yields estimated for the two portions of the watershed were primarily related to annual precipitation patterns.

Measured increases of soil erosion in western Oregon due to timber harvesting and road construction have varied from barely perceptible on gently sloping watersheds with stable soils to 23 times the natural rate on steep watersheds with unstable soils (Fredriksen and Harr, 1979). Erosion rates have generally been found to increase with increasing average slope, largely reflecting greater potential for debris avalance occurrence. Slopes in the Middle Santiam River study area were very steep, although soils developed on the andesitic bedrock were moderately deep, stony and relatively resistant to slope failure. Dyrness (1967) observed that the frequency of landslides in a roaded basin of similar lithology (Sardine formation) was relatively low, even after a 100-year storm event that caused considerably landsliding from roads constructed on the less competent parent materials of the Little Butte formation. Thus, despite the high erosion potential in the study area due to steep slopes, only a moderate increase in sediment yield might have been expected in response to land use because of the relatively competent parent material of the hillslopes.

Swanston and Swanson (1976) and Fredriksen and Harr (1979) further noted that standards of road construction largely determine the rates of erosion from watersheds with high erosion potential. The Oregon Forest Practice regulations under which the study area was managed prescribed guidelines that were primarily aimed at preventing the occurrence of debris avalanche landslides with improved standards of road location, construction and maintenance than were in general use in the region prior to 1972. Although ten road-related landslides did occur in the study area over the period from 1972 to 1980, they were apparently too small (average volume = 900 m^3) and too infrequent to cause long-term changes in sediment yield and water quality in the study area. Although the potential for increasing erosion by deep-seated mass movements such as slump-earthflows or soil creep exists, there was no indication that erosion from these mechanisms had accelerated. The frequency of road-related landslides greater than 50 m^3 during the study period was 0.35 events $km^{-2}yr^{-1}$. (Rates are based on area of total road right-of-way, assuming an average width of 20 m.) This value appears to be similar to the rate of 0.10-0.87 events $km^{-2}yr^{-1}$ (rates varying by time period) for the Middle Fork of the Willamette River in the west Cascades of Oregon reported by Lyons and Beschta (1983). This value is about one-fourth the rate of 1.38 events $km^{-2}yr^{-1}$ reported from roads in the H. J. Andrews Forest in the western Cascades of Oregon (Swanston and Swanson, 1976).

Beschta (1978) noted that potentially unstable watersheds must experience a hydrologic event of sufficient magnitude before an increase in sediment production occurs. Swanson and Fredriksen (1982) estimated that in this region, storms of about a seven-year return period are required to trigger mass failures on clearcut slopes. Presumably more frequent storms could trigger mass failures from roads, since they collect and concentrate storm runoff. The fact that most road-related landslides were associated with new roads and the relatively small storm events that were required to trigger many of them suggest that most road sites with failure potential due to inadequate design or poor location did so fairly rapidly. Road maintenance practices could be playing an important role in minimizing road failures as roads grow older.

Nearly all of the landslides originated on midslope roads and landings that were less than two years old and several coincided with construction. By 1980 more than 50 percent of the roads in the study area were at least five years old, and the frequency of landslides did not appear to be increasing as roads grew older. Beschta (1978) found that most road failures in the Oregon Coast Range occurred within seven years of road construction; Swanston and Swanson (1976) reported that roads less than five years old produced most of the road-related debris avalanches in the western Cascades Range.

Sediments produced from road construction and from road surfaces during log hauling contributed to sediment yield from the study area, but their effect on monthly average turbidity and annual sediment yield was not detected within the natural variability of erosion processes in the basin. Since most road construction sediments probably flush during the first year following construction (Fredriksen, 1970), the sediments produced from road construction could have appeared in streams as early as 1972 and should have peaked as early as 1976, when more than 100 km or road had been built and the rate of construction slowed. Although Reid (1981) has estimated that a heavily used logging road network can potentially increase fine-grained sediment yield as much as 50 percent, Beschta (1978) noted that the natural variability in sediment-discharge relations often make such small changes in sediment concentrations very difficult to detect at a point in the stream system, even with intensive sampling. Indeed, although over 100,000 trips were logged by loaded log trucks during the nine-year study period, suspended sediment yield from the study area (Figure 4) and average turbidity (Figures 5 and 7) did not show increasing trends over the study period with development and use of the road network. Both road surface sediments and construction sediments would be rapidly entrained and washed from road surfaces and channels on the rising limb of storm hydrographs (Reid, 1981). Consequently, much of the road sediment may have been flushed from the stream system early in the storm sequence and its effect on water quality would be more evident at low to moderate flows, as evidenced by the higher probability of measuring positive turbidity differences in this situation. Road sediments added to streams during stormflow could not be separated from background levels of "natural" sediments.

Study results indicate that management activities conducted within forest practice regulations did not produce detectable changes in suspended sediment export that accumulated in time or space. Cumulative effects from basin development on the suspended sediment measured at a downstream point in the watershed were not evident in either the monthly or annual time intervals in which the data have been presented. Landslides that added sediment to streams produced only short-term responses in suspended sediment concentrations at downstream sampling locations. Since landslide events occurred infrequently, there was no overlapping of sediment pulses from one event to another.

The rate at which bedload sediments were moved through the study area after landslides is not known since bedload sediments in the river were not sampled. Channel changes that were documented by Lyons and Beschta (1983) in nearby drainage basins that were due to increased sedimentation such as aggradation and widening were not observed in the Middle Santiam River, based on preharvesting aerial photographs of the study area. Large deposits of coarse sediment were not found along the river or its tributaries except at the junction of the Middle Santiam River and its largest tributary, approximately one kilometer from the eastern order of the study area. This gravel bar, however, was abilized by older vegetation and was easily observable on 968 aerial photographs, suggesting that this deposit may ave been a relic of the large 1964 flood.

The absence of significant long-term increases in sediment xport during basin development and the infrequent occurence of landslides suggests that the forest management techiques used were largely successful in protecting water quality nd minimizing watershed disturbance in the portion of the liddle Santiam River under study. Continuing road mainenance and rapid reforestation of slopes in the study area hould continue to minimize the effects of forest managenent on water quality in the basin.

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LITERATURE CITED

Anderson, Henry W., 1954. Suspended Sediment Discharge as Related to Streamflow, Topography, Soil, and Land Use. Trans. Am Geophys. Union 35(2):268-281.

Benson, M. A., 1968. Uniform Flood Frequency Estimating Methods for Federal Agencies. Water Resources Research 4:891-908.

Beschta, Robert L., 1978. Long-Term Patterns of Sediment Production Following Road Construction and Logging in the Oregon Coast Range. Water Resources Research 14:1011-1016.

Brown, G. W. and J. T. Krygier, 1971. Clearcut Logging and Sediment Production in the Oregon Coast Range. Water Resources Research 7:1189-1198.

Dietrich, William E., Thomas Dunne, Neil F. Humphrey, and Leslie M. Reid, 1982. Construction of Sediment Budgets for Drainage Basins. *In:* Workshop on Sediment Budgets and Routing in Forested Derainage Basins, Proceedings, Frederick J. Swanson, Richard J. Janda, Thomas Dunne, and Douglas N. Swanston (Editors). U.S.D.A. Forest Service, Pacific Northwest Forest and Range Experiment Station, Gen. Tech. Rep. PNW-141, Portland, Oregon, pp. 5-21.

Duncan, S. H. and E. C. Steinbrenner, 1973. Soil Survey of the Calapooya Tree Farm. Weyerhaeuser Company, 86 pp.

Dyrness, C. T., 1967. Mass Soil Movements in the H. J. Andrews Experimental Forest. U.S.D.A. Forest Service Research Paper PNW-42, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 12 pp.

Fredriksen, Richard L., 1970. Erosion and Sedimentation Following Road Construction and Timber Harvest on Unstable Soils in Three Small Western Oregon Watersheds. U.S.D.A. Forest Service Research Paper PNW-104, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 15 pp.

Fredriksen, Richard L. and R. Dennis Harr, 1979. Soil, Vegetation, and Watershed Management. *In:* Forest Soils of the Douglas-Fir Region, P. E. Heilman, H. W. Anderson, and D. M. Baumgartner (Editors). Washington State University Cooperative Extension Service, Pullman, Washington, pp. 231-260.

Geppert, Rollin R., Charles W. Lorenz, and Arthur G. Larson, 1983. Determination of Possible Cumulative Effects of Forest Land Management Activities: A Literature Review. Washington Forest Practices Board, Olympia, Washington, 154 pp.

Guy, H. P., 1969. Laboratory Theory and Methods for Sediment Analysis. U.S. Geological Survey Techniques Water Resources Investigations, Book 5, Chapter C1, 58 pp.

Harr, R. D., 1981. Some Characteristics and Consequences of Snowmelt During Rainfall in Western Oregon. Journal of Hydrology 53: 277-304.

Hicks, Bryan A., 1982. Geology, Geomorphology, and Dynamics of Mass Movement in Parts of the Middle Santiam River Drainage, Western Cascades, Oregon. Unpub. M.S. Dissertation, Oregon State University, Corvallis, Oregon, 169 pp.

Larson, Keith R. and Roy C. Sidle, 1980. Erosion and Sedimentation Data Catalog of the Pacific Northwest. U.S.D.A. Forest Service Pacific Northwest Region, Portland, Oregon, 64 pp.

Lyons, Joseph K. and Robert L. Beschta, 1983. Land Use, Floods, and Channel Changes: Upper Middle Fork Willamette River, Oregon (1936-1980). Water Resources Research 19(2):463-471.

McCashion, J. D. and R. M. Rice, 1983. Erosion on Logging Roads in Northwestern California: How Much is Avoidable? Journal of Forestry, January 1983:23-26.

Patric, James H., James O. Evans, and J. David Helvey, 1984. Summary of Sediment Yield Data from Forested Land in the United States. Journal of Forestry, February 1984:101-104.

Peck, D. L., A. B. Griggs, H. G. Schlicker, F. G. Wells, and H. M. Dole, 1964. Geology of the Central and Northern Parts of the Western Cascade Range in Oregon. U.S.D.I. Geological Survey, Professional Paper 449, 50 pp.

Reid, L. M., 1981. Sediment Production from Gravel-Surfaced Forest Roads, Clearwater Basin, Washington. Rep. No. FRI-UW-8108, Fisheries Research Institute, College of Fisheries, University of Washington, Seattle, Washington, 247 pp.

Swanson, Frederick J. and Richard L. Fredriksen, 1982. Sediment Routing in Budgets: Implications for Judging Impacts of Forestry Practices. *In:* Workshop on Sediment Budgets and Routing in Forested Drainage Basin, Proceedings, Frederick J. Swanson, Richard J. Janda, Thomas Dunne, and Douglas N. Swanston (Editors). U.S.D.A. Forest Service, Pacific Northwest Forest and Range Experiment Station, Gen. Tech. Rep. PNW-141, Portland, Oregon, pp. 129-137.

Swanston, Douglas N. and Frederick J. Swanson, 1976. Timber Harvesting, Mass Erosion, and Steepland Geomorphology in the Pacific Northwest. *In:* Geomorphology and Engineering. Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania, pp. 199-221.

Wolman, M. G., 1977. Changing Needs and Opportunities in the Sediment Field. Water Resources Research 13:50-54.