AN ABSTRACT OF THE THESIS OF

Beverley C. Wemple for the degree of Master of Science in Geosciences presented on January 21, 1994.

Title: Hydrologic Integration of Forest Roads with Stream Networks in Two Basins, Western Cascades, Oregon.

Abstract approved: ______________________________

(Julia Allen Jones)

This study assessed how logging-access roads may have contributed to observed historical increases in peak discharges associated with small and large logged basins in the western Cascades of Oregon. The study was conducted on the Lookout Creek (62km^2) and the upper Blue River (118km^2) basins. Potential road effects on hydrology were examined using a combination of field surveys and spatial modeling with a geographic information system (GIS). Road networks were similar in both basins with respect to hillslope position, orientation, and stream crossings, but roads in Blue River were constructed one or two decades later than roads in Lookout Creek. A total of 20% (62 km) of the road length was sampled to assess routing of surface flow, using 31 2-km transects stratified by decade of construction and hillslope position. Along each transect, ditches and culvert outlets were examined and this information used to predict the probable routing of water to (1) existing stream channels, (2) newly eroded gullies downslope of culvert outlets, or (3) subsurface flow. Nearly 60% of the surveyed road length appeared to route water directly to stream channels

or into gullies. Over time, the length of road connected to stream crossings has decreased, while the length of road discharging runoff that reinfiltrates to subsurface flow has increased, as roads have progressed up hillslopes and onto ridges in Lookout Creek and Blue River. The relatively constant proportion of the road network draining to gullies over time suggests that roads have the potential to become integrated into stream networks, even when constructed on unchannelled hillslope positions. An extended stream network, assumed to exist under storm conditions, was simulated for the basins using a digital elevation model. Although gullies and ditches differ from natural channels, extrapolation of field surveys using the GIS suggested that roads might extend the stream network by as much as 40% during storm events. It is hypothesized that such an effect could decrease the time of concentration of stormflow and contribute to higher peak discharges observed after clearcutting and road construction in these basins. Differences in the magnitude of road effects on peak flow generation may occur among road systems according to hillslope position of roads, road age, soil saturation, geologic substrate, and climate. These differences may explain the range of observed results from paired-basin studies examining road effects on hydrologic response.

Hydrologic Integration of Forest Roads with Stream Networks in Two Basins, Western Cascades, Oregon

by:

Beverley C. Wemple

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed January 21, 1994

Commencement June, 1994

APPROVED:

Associate Professor of Geosciences in charge of major

Chairman of department of Geosciences

Dean of the Graduate School

Date thesis is presented: January 21, 1994

Typed by: Beverley C. Wemple

Acknowledgments

The list of individuals to whom I owe acknowledgment is testimony to the quality of guidance and assistance that I have had throughout this experience. First, and foremost, I wish to thank my advisors Julia Jones, Gordon Grant, and Fred Swanson, under whose mentorship and support my interests in geomorphology and hydrology have developed. I have also greatly benefited from discussions with Leslie Reid, Dave Montgomery, Bob Beschta, and Walt Megahan.

Numerous individuals provided support in the completion of this study. George Lienkaemper and Barbara Marks provided assistance with GIS analysis. Fred Ramsey guided me in statistical analysis and interpretation. Brian Kramer, Marv Pyles, Roy Silen and Connie Risely were immensely helpful in educating me on the intricacies of forest-road planning and design. Al Levno, Greg Downing, Craig Creel, and John Moreau provided guidance and assistance in field work. I also thank Reed Perkins and Christine Roberts for their enthusiastic assistance with field work. Thanks are due to Fred Friedow and Katie Farrell for assistance with various admistrative matters.

Finally, this work cannot be put to rest without expressing gratitude to my family. My husband, Bryan, has supported me emotionally, financially, and psychologically through this grueling process and has encouraged me to pursue my dreams. To my parents I owe special thanks for the sacrifices and support that have made my education possible.

Funding for this research was provided through a cooperative agreement between the USDA Forest Service, Pacific Northwest Research Station and Oregon State University. This was a contribution of the H.J. Andrews Experimental Forest Long-term Ecological Research program (National Science Foundation grant BSR 90-111663) and the USDA Forest Service Ecosystem Management Program. Additional funding for completion of this work was provided through a grant from the Cooperative Research Branch of the USDI Bureau of Land Management (Agreement No. H952-A1-0101-19).

Table of Contents

APPENDICES

List of Tables

List of Figures

Hydrologic Integration of Forest Roads
with Stream Networks in Two Basins,
Western Cascades, Oregon

I. INTRODUCTION

Roads represent a pervasive, persistent and potentially cumulative form of landscape impact on steep forested land. Road construction and use have been shown to have measurable effects on a range of geomorphic processes. Increased sediment delivery to streams has been documented following road construction on forested lands (Sullivan and Duncan, 1981; Reid and Dunne, 1984). Forest roads have been shown to affect slope stability, often increasing the rate of mass failure on hillslopes (Swanson and Dyrness, 1975; Megahan et al, 1978; Lyons and Beschta, 1983; Swanson et al, 1987). Earlier and recent data-rich studies indicate that roads may be substantial contributors to increased peak flows in small (10^2 hectare) and large (10^5 hectare) basins (Harr et al, 1975; Harr et al, 1979; King and Tennyson, 1984; Jones and Grant, in prep, a and b) The impacts of roads on sediment and water can result in changes in channel morphology, which in turn may affect fish habitat and water quality (Cederholm and Salo, 1979).

Recent attention given to the cumulative effects of forest-harvesting activities has highlighted the need to understand the effects of roads on hydrologic processes (Forest Ecosystem Management Assessment Team, 1993). Paired-watershed experiments provide information on the range of possible effects of roads on streamflow and sediment for basins up to 5 km^2. Little work has been done, however, to evaluate the cumulative effects of a road network on geomorphic and hydrologic processes over time for larger geographic areas.

This study was designed to examine some aspects of possible road effects on stream networks in study basins where retrospective studies of 40 years of peak flow data reveal significant and substantial peak flow increases following road construction and forest harvesting (Jones and Grant, in prep, a and b).

This thesis represents an effort to combine basic information on the historical development of a road network with field observations and spatial data to describe hydrologically relevant effects of an extensive road system, and thus the potential impact on hydrologic processes. The primary objective of this research was to use field observations to formulate hypotheses about the landscape-level effects of a road network on streamflow generation and routing in order to begin to evaluate the long-term, cumulative effects of a road network in forested lands.

II. BACKGROUND

Relevant background for an examination of the hydrologic effects of roads includes an understanding of road network development on forest lands, an introduction to fundamental aspects of road design and drainage, and evidence from studies conducted at various spatial and temporal scales revealing the range of effects of roads on streamflow. These topics are presented below to provide context for work conducted for this study.

A. Road Planning and Development in Pacific Northwest Forests

There is little historical documentation in the literature on the evolution of forest road networks. While much of the literature on forest roads addresses the economics of road system planning (Carow and Silen, 1957; Silen and Gratkowski, 1953; Sessions, 1986), some principles that have governed road system development in Pacific Northwest forests emerge from various sources.

In general, forest road systems are planned in accordance with the intended method of timber harvesting (Sedlak, 1985). Other factors that influence the layout of a road system include distribution of harvestable timber, equipment constraints, topography and slope stability, climate, and watershed management considerations, such as siltation to streams during construction (Ruth and Silen, 1950; Sedlak, 1985). The role of economics in road development is also a critical factor. Optimization of available technology and minimization of costs are the principle economic concerns in road development. Long-term harvesting strategies, infrastructure requirements for timber access, and economic objectives of the landowner play important roles in development of forest road networks (Sessions, 1986).

The historical pattern of road network development in the Pacific Northwest, as in other areas, is closely related to the available technology for yarding and hauling logs. In the Lookout Creek basin, where this study was conducted, tractor and high-lead yarding systems were the primary harvesting methods used during the 1950's and early 1960's when most of the roads were constructed (Carow and Silen, 1957). Optimum yarding distances ranged between 400 and 900 feet for high-lead and between 500 and 1400 feet for tractor yarding. Optimum road spacings (e.g. average horizontal distance between roads on a hillslope) to accommodate these yarding systems ranged from 1000 to 1600 feet (Ruth and Silen, 1950; Silen, 1955).

By the late 1960's and early 1970's, several developments led to a general trend in the construction of ridgetop roads with higher grade approaches. First, a recognition of slope stability concerns and the apparent high rate of mass failure associated with midslope roads (Jensen and Cole, 1965; Dyrness, 1967; Swanson and Dyrness, 1975; Megahan et al, 1978) encouraged the construction of ridgetop roads (Sessions et al, 1987). Second, the availability of skyline yarding systems, and more recently balloon and helicopter systems, permitted harvest and yarding over long hillslope distances (in excess of several thousand feet) without intermediate roads and landings (M. Pyles, OSU Dept. of Forest Engineering, personal communication, June 1993). Finally, the advent of more efficient vehicles, geared for higher grades and equipped with air-compressor brake systems, permitted the construction and use of steeper roads for ridgetop access (Anderson et al, 1987; M. Pyles, OSU Dept. of Forest Engineering, personal communication, June 1993).

In a review of studies investigating road impacts in forested landscapes, Megahan (1972) showed that the percent of harvested area occupied by roads ranges from 30% for tractor and jammer logging systems to 1% for helicopter systems, reflecting a decline in road density with advancing technology and growing environmental concerns. Analysis of the impacts of forest roads should therefore be viewed in their historical context. In summary, historical trends in road development have reflected four fundamental factors: (1) available harvesting methods, (2) technological advances, (3) environmental concerns, and (4) economic considerations.

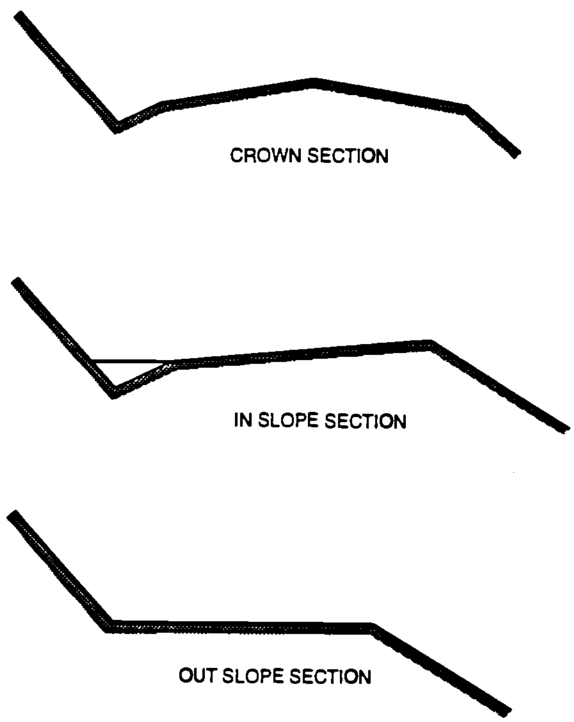
B. Road Design and Drainage

Aspects of road design relevant to this research include not only the evolution of road locations in forested basins, as discussed above, but also the design and function of road drainage systems. Figure 1 illustrates terminology and aspects of road design and drainage relevant to this study.

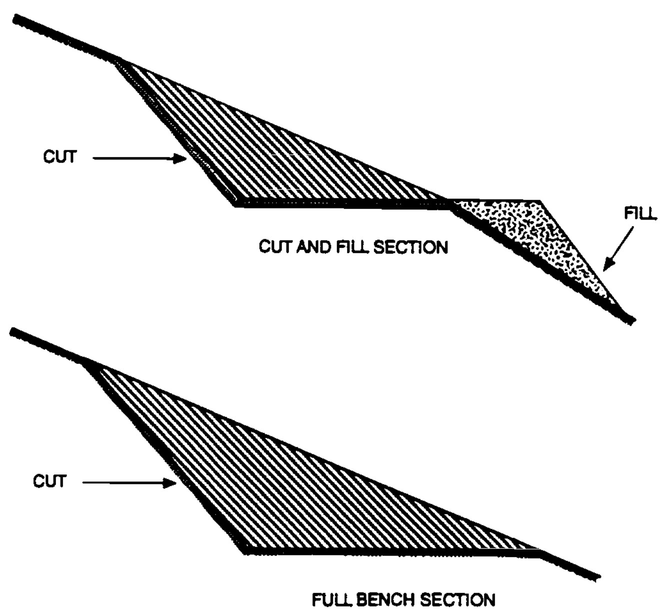
Three road surface templates are used in forest road design (Figure 1a). Both crowned surface and in-sloped surface templates require a ditch for drainage of surface runoff. While outsloped roads do not require a ditch, ditch-relief culverts, or drainage maintenance, this design is not generally used for grades over 9% and is often not recommended due to safety considerations (Kramer, 1993). Slope excavation for forest roads is either by cut and fill, where hillslope material is excavated and used to support part of the road bed, or by full-bench endhaul, in which the entire road bed is constructed on the excavated surface and excavated material is deposited offsite (Figure 1b). Roads constructed in Lookout Creek and Blue River, the study sites for this research,

Figure 1: Road design

(a) Road-surface templates



(b) Slope excavation for road construction



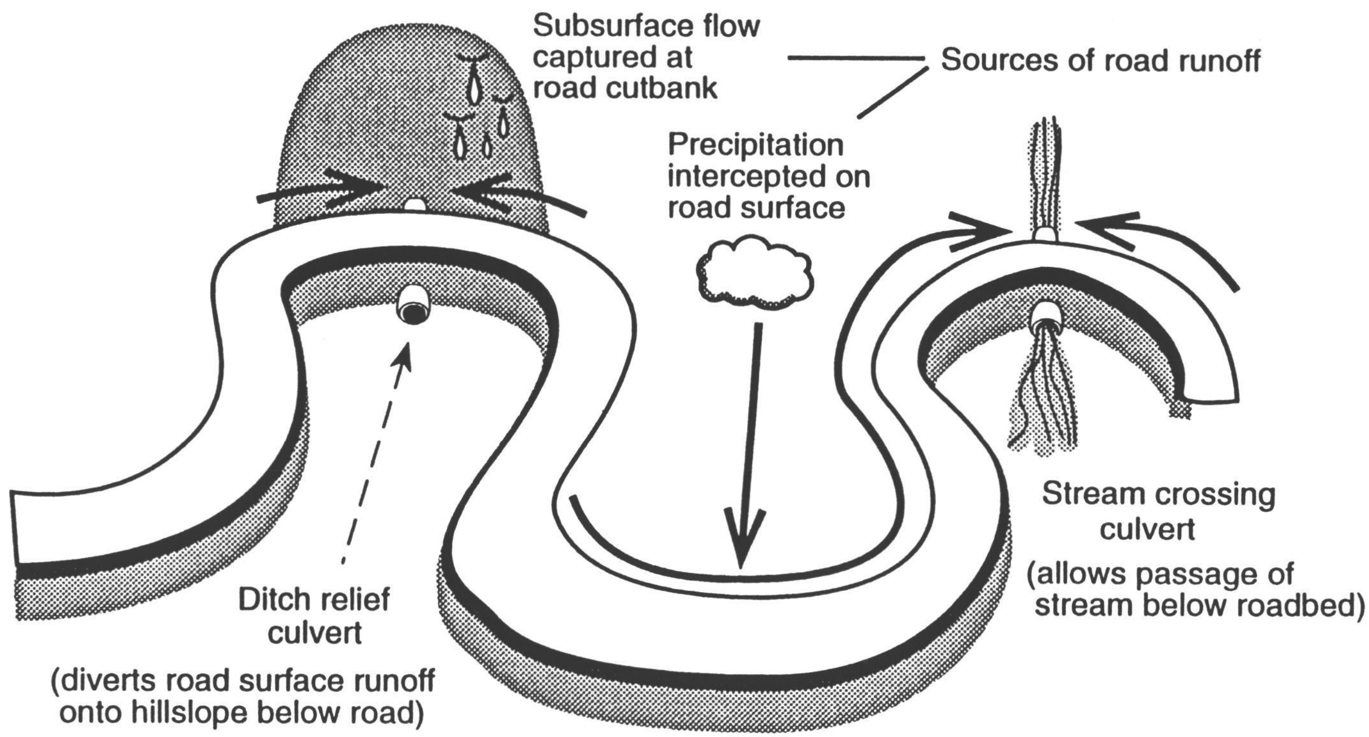
are largely insloped, cut-and-fill roads with inboard ditches (L. Bates, Engineering Staff, Blue River Ranger District, Willamette National Forest, personal communication, September 1992). Most of the road network in these basins was constructed before full-bench construction was common.

Culverts are an important feature of the road drainage system. They are designed to route surface runoff away from the road bed and ditch in an efficient manner. Culvert installations may be classified into two types: (1) ditch-relief culverts designed to discharge surface runoff from the roadside ditch to the hillslope below the road, and (2) stream-crossing culverts placed where the road crosses a stream (Figure 2). Because these two kinds of culverts are designed to function differently in routing surface runoff, they are treated separately in the design of field observations and in the presentation of results in this study.

Federal guidelines for stream-crossing culverts are specified in the Road Drainage Structures Handbook (USDA Forest Service, 1986). Pipe sizing is based on an economic analysis of installation and maintenance cost, risk of failure and attendant environmental concerns, and public safety considerations. In Oregon, state forest practices rules require that stream-crossing culverts be designed to handle a peak flow of 25-year recurrence interval (Oregon Department of Forestry, 1991). Pyles et al (1989) provide a comprehensive summary of design considerations for stream crossing culverts. In addition, their assessment of culvert installations in the Oregon Coast and Cascade Ranges indicated that many culvert installations failed to meet the minimum recurrence-interval design standard specified by the Oregon State Forest Practices rules (Pyles et al, 1989).

Guidelines for the spacing of ditch-relief culverts on federal lands are specified in the Road Preconstruction Handbook (USDA Forest Service, 1987) and include consideration of road gradient, surface material, soil type, runoff

Figure 2: Road runoff and drainage



characteristics and the effects of water concentration on slopes below the road. While these guidelines exist, local experience and engineering analysis of site-specific conditions generally govern the placement of ditch-relief culverts (Kramer, 1993; R. Kellison, Engineering Staff, Blue River Ranger District, Willamette National Forest, personal communication, August 1993). In a study of road drainage performance in the central Oregon Coast Range, Piehl et al (1988) found that no consistent procedure had been used for the spacing of ditch relief culverts.

In general, road design practices are highly site-specific. Federal and state guidelines specify minimum standards. Actual practices, however, are based largely on the experience and expertise of engineering personnel.

C. Road Impacts on Hydrology

1. Localized Effects of Roads

Roads have been shown to affect runoff generation by two primary mechanisms (Figure 2). First, compacted road surfaces limit infiltration and thus have the potential to generate surface runoff, which is rare for undisturbed soils in western Oregon, thereby speeding delivery of water to the stream network in roaded portions of the basin. Second, slow subsurface flow may be captured along road cutbanks and transformed to more rapid surface runoff. These changes in flow routing due to roads may alter the timing of water delivery to streams, with the potential to either increase or decrease peak flows.

Site-specific studies provide data on the magnitude of these two sources of road-related runoff. Average infiltration capacities for forest road surfaces have been estimated to range from 0.5 mm/hr (Reid and Dunne, 1984) to 0.11 mm/hr (Luce and Cundy, 1994, ms in press). Rainfall simulation studies have shown that runoff/rainfall ratios on roads range from an average of 55 to 80% for dry antecedent conditions to an average of 81 to 100% for wet antecedent conditions (Burroughs et al, 1984; Foltz and Burroughs, 1990). Sullivan and Duncan (1981), in a study in western Washington, found that culvert outflow was 50-185% of precipitation falling on the roaded area. The lower estimate indicates that as much as 50% of precipitation infiltrated the road and ditch surfaces, while the higher estimate indicates that appreciable amounts of intercepted subsurface flow also contributed to ditchflow.

Megahan (1972) estimated that the volume of subsurface flow captured at road cutbanks on a study site in Idaho was seven times greater than runoff from road surfaces. He also estimated that 65% of the subsurface flow passed beneath the roadbed. In other words, the road cut was effective in capturing only 35% of the estimated volume of water moving as subsurface flow in the hillslope (Megahan, 1972).

Results of these studies indicate that roads serve as sources of surface runoff in forested basins, but that the volume of road runoff originating from intercepted precipitation and captured subsurface flow is highly variable. The magnitude of road-related runoff is controlled by many factors. Road surface runoff is related to the permeability of road surfacing materials (Sullivan and Duncan, 1981) and antecedent moisture (Burroughs et al, 1984; Foltz and Burroughs, 1990). Subsurface-flow interception may be related to depth to bedrock, soil porosity, degree of soil saturation, and magnitude of the storm event (Megahan, 1972).

The connectivity of the road drainage system to the channel network determines the extent to which road-generated runoff exits the basin as quick flow. Detailed road surveys have shown that a large percentage of culverts on forest roads are positioned at perennial or intermittent streams (Bilby et al, 1989; Irvin and Sullivan, unpublished report as cited in Duncan et al, 1987), thereby discharging road runoff into natural drainage courses. Sediment studies have implicated road surfaces as a significant sediment source to stream channels (Megahan and Kidd, 1972; Reid and Dunne, 1984; Sullivan and Duncan, 1981), providing further evidence of the integration of roads with the channels to which they deliver sediment. In addition, studies evaluating road drainage structures (e.g. culverts) have documented substantial erosion below culvert outlets (Piehl et al, 1988; Ricks, Siskiyou National Forest, unpublished data). Extensive gully erosion associated with road drainage failure at Redwood Creek, California, has led to changes in drainage density and channel geometry (Hagans et al, 1984). In short, previous research on the effects of forest roads provides evidence that the drainage system accompanying forest roads interacts with the naturally occurring channel network to modify surface flowpaths, discharging road runoff and associated sediment directly into streams.

2. Basin Experiments

Numerous studies have examined the impact of forest roads on hydrology in steep, forested lands (Table 1). Results of small basin studies show little effect of roads on water yield. The demonstrated effect of roads on peak flows is highly variable, with individual studies showing an increase, decrease or no change in peak flows after road construction. Rothacher (1965, 1970) detected no significant increase in annual water yield or peak flow due exclusively to roads

Table 1: Experimental watershed studies examining effects of roads on streamflow

Study	Watershed	area (ha)	% area logged	% area in roads	monitoring history	results
Rothacher,	HJA Exp For, OR				calibrated 1952-59	no increase in peak flows in WS 3 after 8% area cleared and
1965,	WS1	95.9	100%	0	roads in WS3 1959	roads constructed; significant increase mean peak flows after
1970,	WS2	60.7	control	0	harvest began 1962	road plus 25% patch cut; 12-28% increase in summer
1973	WS3	101.2	25%	8%		lowflows during 6 yrs after roads & logging (1959-64)
Harr et al,	Alsea, OR				large WS's calibrated 7	peak flows increased significantly on basin with 12% in roads
1975	Deer Cr	303	25%	4%	years (1958-1965)	greatest total changes in peak flow, quick flow & total storm
	Flynn Cr	203	control		SubWS's calibrated 3 years	hydrograph vol. detected on basin where 82% CC and 5% in
	Needle Br	70.8	82%	5%	(1963-65)	roads
	Deer Cr SubWS2	55.9	30%	3%	roads 1965	
	Deer Cr SubWS3	40.5	65%	12%	harvest began 1966	
	Deer Cr SubWS4	15.8	90%			
Harr et al,	Coyote Cr, OR				calibrated 5 years (1964,	peak flow increased 48% at CCr1, 35% at CCr3, 11% at
1979	CCr1	69.2	50%	1.6%	1966-70)	CCr2
	CCr2	68.4	30%	1.7%	roads 1970	annual yield increased 43% on CCr3, 14% on CCr2, 8% on
	CCr3	49.8	100%	0.3%	harvested 1971	CCr1
	CCr4	48.6	control			
Ziemer,	Casper Cr, CA				calibrated 1963-67	smaller peak flows from fall storms were increased about
1981	SoFk	424	100%	5%	roads 1967	300% after logging; no significant increase in winter & spring
	NoFk	508	control		harvesting 1971-73	peaks; no significant increase attributed to roads.
King &	Horse Cr, ID				calibration began 1975	significant increase in 25% exceedance flows (representing
Tennyson,	WS6	103.6		control	roads on WS8,16,18 in	snowmelt runoff & few summer storms) in WS12 with 3.9% in
1984	WS8	147.7		3.7	1978	roads. Increase was 30.5% greater than expected.
	WS10	65.2		2.6	roads on WS10,12,14 in	
	WS12	83.8		3.9	1979	significant decrease in 5% exceedance flows (representing
	WS14	62.3		1.8	harvesting on each WS 2	18 highest days of flow, usually during snowmelt runoff) in
	WS16	28.3		3.0	yrs after road construction	WS18 with 4.3% in roads. Decreases were 29.4% and
	WS18	86.2		4.3	WY1975-80 evaluated	19.2% greater than expected in 1979 and 1980.
Wright et al,	Casper Cr, CA	see				runoff volumes and peakflows increased for smallest storms
1990	SoFk	Ziemer				only (peaks < 566L/s)
	NoFk	1981				
Jones &	HJA Exp For, OR	see				road construction prior to clearcutting increased peak
Grant, in	WS1	Rothacher,				discharge, advanced time of peak, increased time to peak,
prep, a	WS2	1963				and increased duration of storm hydrograph. All changes
	WS3					were not statistically significant.

in paired experimental 0.6 to 1 km^2 basins of the Lookout Creek drainage in the western Oregon Cascades. Regression analysis by Rothacher (1973) indicated a decrease in peak flows in watershed 3 of Lookout Creek for the three years following road construction. Jones and Grant (in prep, a), using new analysis techniques and an extended record from these basins, found distinct, detectable differences in hydrograph shape in the clearcut basin without roads as compared to the basin with roads and a subsequent 25% patch cut (Table 2). Harr et al (1975) found significant increases in peak flows on Deer Creek watershed 3 of the Alsea basin in the Oregon Coast Range, where roads covered more than 12% of the subbasin area. On the 0.5 to 0.7 km^2 Coyote Creek watersheds in southwestern Oregon, the magnitude of peak flow increases appeared to be related to the watershed area compacted by roads, skid trails and landings (Harr et al, 1979). No increase in peak discharge was detected due to roads covering 5% of the 4.2 km^2 Casper Creek watershed in northern California (Ziemer, 1981). Also, no increase in annual peak flow or annual water yield was apparent due to roads covering 2 to 4% of 0.3 to 1.5 km^2 basins in north central Idaho, although an increase in the 25% exceedance flow occurred on one basin and a decrease in the 5% exceedance flow occurred on another (King and Tennyson 1984).

There are several possible explanations for the varied results from paired-basin studies of road effects on streamflow. First, in the Casper Creek basin studied by Ziemer (1981) and Wright et al (1990), 88% of the 6.8 km road was constructed within 61 meters of the main channel. While road-surface runoff effects might be high here, subsurface-flow interception effects might be substantially lower than in other basins. Second, as suggested by Wright et al (1990), the absence of large stormflow data during the calibration period of the Coyote Creek study (Harr et al, 1979) and during the postcutting period of the Alsea study (Harr et al, 1975) may be responsible for the statistically significant effects of roads demonstrated in both studies. Wright et al (1990) showed in their study that peak flows increased only for the smallest storms (peaks < 566 L/sec), and that roads may alter peak flows only for relatively small storms. Most importantly, none of these studies examined road effects for more than four years, or over a basin larger than 5 km^2. These paired-basin studies have been designed only to monitor the immediate effects of roads, while longer-term cumulative effects have not been isolated from the effects of harvesting (Reid, 1981). Cost, logistical requirements, and legal restrictions on large-scale manipulation constrain the experimental evaluation of long-term cumulative effects of forest harvesting on streamflow.

No published studies have explicitly considered how road networks alter the routing of water through a basin. Considered collectively, published studies of road effects in small (< 5 km^2) basins do not demonstrate the circumstances under which road networks significantly alter the routing of water through a basin. These studies also do not clarify which portions of the landscape, when roaded, are most likely to affect water delivery to stream channels.

3. Large Watershed Studies

Long-term hydrologic studies on large watersheds (>50km^2) have focused on the combined effects of harvest-related activity on streamflow. Mechanisms responsible for changes in streamflow may be difficult to interpret over large geographic areas, where multiple actions (e.g. road construction and cutting) have been implemented and experimental control has not been exercised. Long-term changes in streamflow associated with forest harvesting have been attributed to (1) reduction in evapotranspiration demand after removal of vegetation (Hibbert, 1967; Rothacher, 1971), (2) channel simplification through the removal of large wood from streams (Jones and Grant, in prep, a), (3) greater snow accumulation and melt rate in clearcut patches (Harr, 1986), and (4) road effects on soil compaction, generation of overland flow, and the subsequent rapid delivery of water to streams (Harr et al, 1975; Jones and Grant, in prep, a and b).

In the Pacific Northwest, Anderson and Hobba (1959) used regression analysis to evaluate the effects of forest harvesting and road construction on flood peaks for harvested and undisturbed basins ranging in size from 15 to 19,000 km^2. Their analysis indicated trends of higher peak flows in harvested basins relative to undisturbed basins for the period of record examined. They proposed that reduction in evapotranspirative demand and changes in snow accumulation and melt in clearcut patches were the causal mechanisms for the changes observed.

Christner and Harr (1982) examined the effects of harvest-related activities on peak flows for three pairs of adjacent watersheds (60 km^2 to 600 km^2) in western Oregon. Their analysis showed changes in peak flows corresponding to differences in areas harvested and in roads. They attributed this effect to the rain-on-snow mechanism.

Duncan (1986) used regression analysis to examine the effects of harvesting on peak flows for two fifth-order basins in western Washington. Results of the analysis showed no significant change in peak flows associated with harvesting activity for the period examined. Connelly et al (in prep) hypothesized that the lack of a statistically significant effect of cumulative harvest on peak flows in the Duncan study may be due to the fact that only 10% of the basin harvested during the study period was located within the transient snow zone.

Jones and Grant (in prep, b) reexamined the basins studied by Christner and Harr (1982) using 150 to 200 paired storms spanning a period of record of more than 55 years. Their results indicate a significant increase in peak discharge of $0.14 m^3/s/km^2$ for a difference of 10% in the cumulative percent of basin harvested for all three basin pairs. In the Lookout Creek and Blue River pair this change represents a 20% increase in the median (1-2 year return interval) storm flow, a modest change in relatively frequent storms. Jones and Grant (in prep, b) found no difference in peak flow response for rain versus rain-on-snow events, and hypothesized that the observed trend of increasing peak flows may be associated with a number of mechanisms acting concurrently, including changes in flow routing by roads.

III. APPROACH

Assessing the hydrologic effects of forest roads or other landuse activities poses unique challenges. The impacts of roads constructed over decades are confounded with other landuse impacts, particularly those of cumulative forest harvesting. The apparent magnitude of the effect may also change as the scale of investigation changes, reflecting a shift in the role of the dominant physical processes at different spatial and temporal scales. Finally, the cost and logistical complexity of experimental manipulation to examine the effects of landuse activities requires the formulation of testable hypotheses at scales relevant to the management of large watersheds. This study was developed in light of these issues, employing an observational study to broaden the scale of investigation of road impacts on hydrologic response in forested watersheds of the Pacific Northwest.

A. Conceptual Framework

A number of approaches, ranging from observational to experimental, will ultimately be required to fully assess the cumulative hydrologic effects of roads in forested landscapes. Table 2 displays proposed components of a framework for examining comprehensively the long-term cumulative effects of forest road networks. The framework begins with observational study for exploratory analysis. Observations form the basis for hypotheses and the examination of potential hydrologic mechanisms controlling the effects of roads. This study encompassed these first two phases of this framework: observational study of roads and road drainage to assess the potential effect of roads on streamflow.

Table 2: Conceptual framework for examination of the effects of roads on streamflow.

	exploratory analysis	*examination of potential effects*	*inference of probable effects*	
field observations/ experimentation	observe trends in road development on hillslopes over time and in different basins	conduct field observations of roads in various parts of the basin to examine differences in flow routing; measure the magnitude of possible drainage network modification on a representative sample of roads	conduct measurements of flow in ditches, roughness characteristics, length of newly formed gullies, extent of rainfall interception on road surfaces and subsurface flow capture along cutbanks	experimental manipulation by constructing or removing roads in a paired basin approach; measure change in discharge relative to unmanipulated basin. (limited by temporal and spatial scale of experiment)
spatially explicit modeling	use GIS analysis to determine spatial distribution of roads over time	use field estimates of flow routing on roads to estimate extent of drainage network modification by roads throughout the entire basin	construct, apply and validate a spatially distributed hydrologic model to measure effects of roads and natural channels on routing of water and subsequent influence on peak flows (limited by model accuracy and availability of landuse and streamflow data to validate/test model, before using it to assess effects)	

Definite Conclusions

Further study through modeling of streamflow and experimental manipulation will strengthen inferences about the effects of roads on streamflow and other processes. Definitive conclusions with respect to the cumulative hydrologic effects of roads may only be reached through a combination of process-oriented experimentation and modeling.

The importance of observational study in scientific investigation is addressed by Holland (1986) who argues that formal theories of causation must begin with observation of the effects of given phenomena. Scientists investigating the effects of human action on the environment are often limited to observational studies in which the inferred causal mechanisms are not subject to the control of the researcher (Eberhardt and Thomas, 1991). Application of an experimental approach to such questions is complicated by several factors: environmental phenomena vary continuously in time and space; perfectly controlled replicates and treatments may be impossible to achieve; the cost of experimental manipulation may be prohibitive at early stages of investigation; and often the phenomena of interest occurred under unknown past conditions. Under these circumstances, observational studies may be most appropriate. Through such observation, hypotheses may be formulated. These hypotheses then provide an appropriate context for strengthening our understanding of causal inference with subsequent experimental manipulation or analytical modeling.

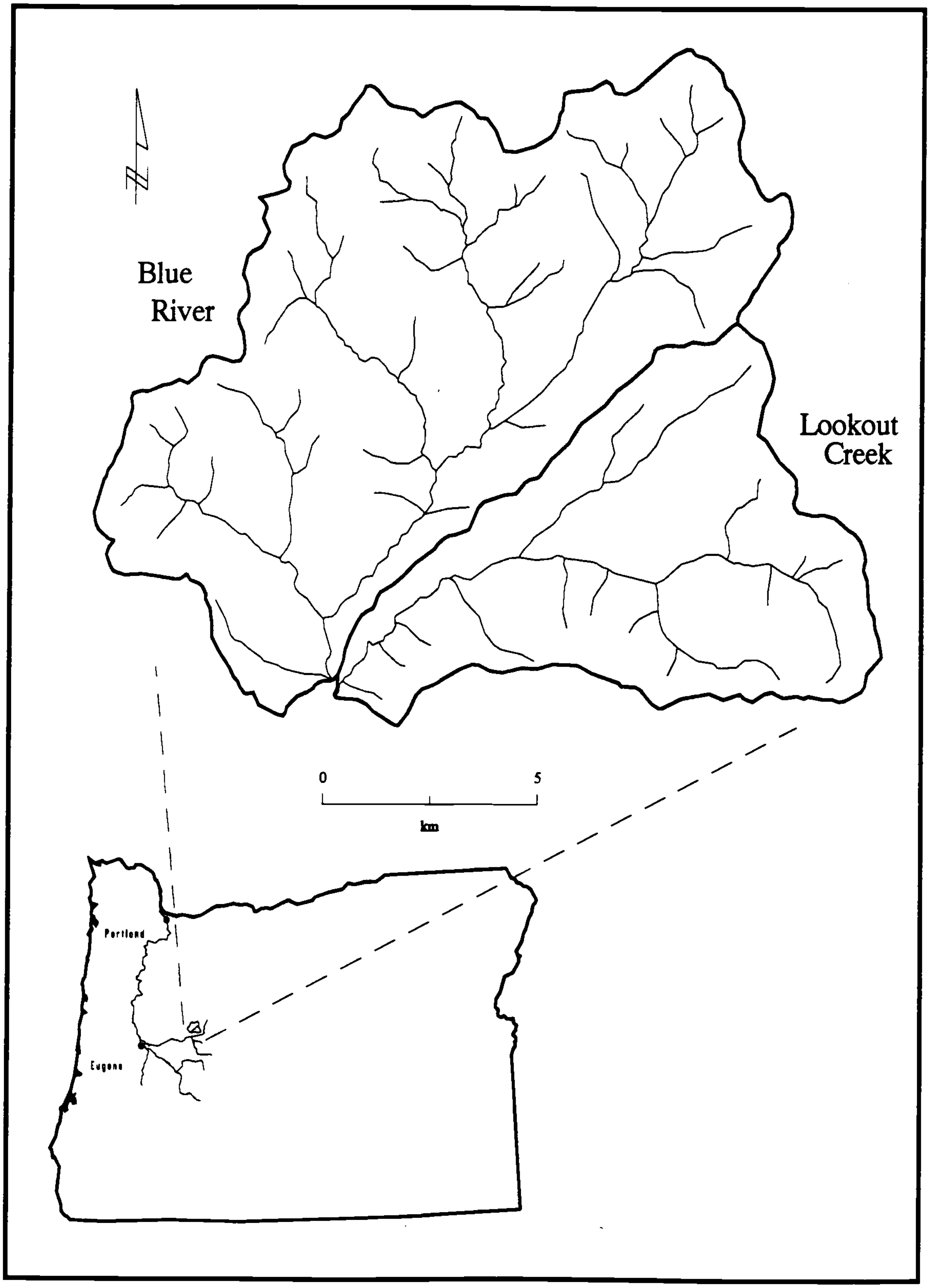
Studies in landscape ecology have demonstrated that certain landscape patterns can provide insights into ecological processes that are not directly observable (see Boots and Getis, 1988). Recent work in landscape ecology has focused on understanding the effect of landscape patterns on ecological processes (Turner, 1989). These concepts, though largely developed in the biological and ecological disciplines, can also provide a context for the study of physical processes. While the complexity of certain physical processes may not lend itself to direct observation, observable patterns, trends or physical features may lend insight into the process of interest. In this study, the pattern/process linkage was employed in several respects by posing the following questions: what is the historical trend of road development in space and time; do the historical trends in road development appear to be associated with observed changes in streamflow over time; are there observable features of the road network that indicate how roads function hydrologically; and what is the magnitude of the apparent road effects on hydrologic processes?

Landscape ecology has also placed considerable emphasis on selecting relevant scales which incorporate the spatial and temporal domains of interest (Wiens, 1989). The apparent importance of processes that operate at one spatial or temporal scale may be diminished or enhanced as the scale of interest changes. Previous investigations of the specific hydrologic effects of roads have largely been conducted at spatial scales of <5 km^2 and over time scales of one to ten years. In this research, the temporal and spatial scales of investigation were broadened, recognizing that road effects can no longer be isolated from other landuse effects, but nevertheless attempting to understand how an extensive road network functions hydrologically.

B. Study Area

The study area consisted of Lookout Creek (62 km^2) and Blue River (119 km^2) basins, two adjacent fifth-order basins located approximately 70 km east of Eugene in the western Cascades of Oregon (Figure 3). Lookout Creek is the site of the H.J. Andrews Experimental Forest, where a long series of paired basin

Figure 3: Study area



experiments have assessed the effects forest harvesting and roads on small basin hydrology, sediment yield and other processes (Rothacher, 1965, 1970, 1971, 1973; Jones and Grant, 1993a). The basins lie within the western hemlock zone (Franklin and Dyrness, 1969), with Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) predominating.

Elevations in the two basins range from 400 meters to over 1500 meters with slopes ranging from 20 to over 80%. Average annual precipitation is approximately 225 cm (Greenland, 1993), falling typically as rain between October and May at the lower elevations and as snow at higher elevations (Berntsen and Rothacher, 1959). Peak flow events are often associated with the rapid melt of shallow snowpacks during warm rain events (Harr, 1976; Harr, 1981).

The present geomorphic structure of the basins has been shaped by a complex suite of glacial, fluvial and mass wasting processes (Dyrness, 1967; Swanson and James, 1975). The basins are underlain by geomorphically unstable, hydrothermally-altered, volcaniclastic rocks in the lower elevations and by stable lava flows at higher elevations (Swanson and James, 1975). The three principle soil types include (1) a residual clay loam, derived from andesites and basalts, on steep slopes and ridges in the upper portions of the basins, (2) a residual silty clay, derived from agglomerates, tuff and breccia, comprising the relatively unstable material found largely on midslope and low-ridge areas, and (3) a clay loam, originating from colluvial materials, on gentle slopes and benches (Berntsen and Rothacher, 1959). Colluvial deposits as deep as 50 feet underlie soils in some portions of the basins (Dyrness, 1969).

Soil infiltration capacities are extremely high and Hortonian overland flow rarely occurs on undisturbed forest floors (Dyrness, 1969). The movement of water through the subsurface accounts for nearly all streamflow from forested watersheds here, as in most areas of the western Cascades (Harr, 1976; Harr, 1977).

Construction of logging roads and forest harvest began in Lookout Creek in the mid 1940's and in Blue River in the mid 1950's and expanded throughout the following decades. By 1990, nearly 25% of each basin had been harvested (Jones and Grant, in prep b). Currently 3% of each basin is occupied by roads (Table 3).

Table 3. Physical characteristics of the study basins

	Lookout Creek	Blue River
1. Basin area (km^2)	62	119
2. Road length (km)	119	230
3. Road density (km/km^2)	1.9	1.9
4. Area of basin in roads (%) [a]	3.1	3.1

[a] computed using average width of road and cut and fill of 59.9 ft (16m) after Silen and Gratkowski, 1953.

C. Study Design

Road networks have the potential to generate surface runoff and alter the routing of storm flow by three distinct mechanisms: (1) intercepting precipitation on compacted road surfaces, (2) capturing subsurface flow along road cutbanks, thereafter channeling water as surface runoff through roadside ditches and onto hillslopes or into channels below the road, and (3) routing surface runoff through newly-incised channels below some culvert outlets. Examination of the road drainage system was conducted in this study to provide data on the contribution of surface runoff to streams and an indication of the functional integration of road and stream networks.

In order to examine the hydrologic role of the extensive road network constructed in the study basins over a period of more than four decades, the study was designed with three major elements:

1) An historical analysis of road network development in Lookout Creek and Blue River;
2) Field studies to estimate the degree to which road segments function as new channel segments integrated with the natural stream network, thereby increasing channel-network efficiency;
3) Extrapolation of field results to the entire basins using a geographic information system (GIS) to infer road impacts on hydrology.

The fundamental goal of the study was to examine mechanisms for road impacts on the routing of water in the study basins and to estimate the apparent impact of any effect.

D. Methods

1. Historical Road Network Analysis using GIS

Road network data for the Lookout and Blue River basins were compiled and digitized from aerial photographs using the AP190 analytical stereoplotter (Kiser, 1992). Full details of data automation are given by Jones and Grant (in prep, b). Digitized data were exported to the Arc/Info geographic information system (Environmental Systems Research Institute, Redlands, CA) for attributing and analysis. Historical analysis of road development was conducted with two objectives: (1) to determine whether any substantial differences existed in the temporal or spatial distribution of roads in Lookout Creek and Blue River that might explain historical changes in streamflow observed by Jones and Grant (in prep b), and (2) to determine the spatial and temporal configuration of roads in the study basins in order to select roads for field sampling in proportion to their actual distribution.

Digital elevation models (DEMs) for the study area were processed in Arc/Info to develop slope and elevation data layers. In a two step process, raw DEM data were converted to Arc lattice files, then processed to create slope and elevation polygons. Road network expansion through time, road length in 100 meter elevation classes, and road length on slope classes were determined for the study basins using GIS overlay analyses and statistical tabulations.

Road length in various hillslope positions was approximated using buffer techniques on several geographic features. A 100 meter buffer around the main-stem of Lookout Creek and Blue River was constructed and used to calculate road length in valley bottoms over time. To estimate road length on ridgetops, the boundaries of basins ≥ 100 hectares were buffered by 100 meters and overlain with roads to calculate road length on ridges over time. While buffers on basin boundaries are not a precise measure of ridges, these data were used only to approximate road development trends.

2. Field Data Collection

a. Sampling Design

Roads were sampled in a stratified design based on road age and hillslope position. Twenty percent (20%) of the total road length constructed in each decade between 1950 and 1990 was selected for field sampling, for a total of 31 transects (62 kilometers of road). The designated number of transects was further stratified by hillslope position proportional to the relative length of road constructed during each decade in valley bottom, ridgetop and midslope positions (Table 4). These hillslope positions were defined by areas within the main-stem Lookout Creek/Blue River buffer described above, the basin-outline buffer which roughly approximates ridgelines, and all remaining areas, respectively. The starting point for each transect was randomly selected at road junctions or road ends that could be located both in the field and on maps. Figure 4 shows locations of the 31 two-kilometer transects sampled.

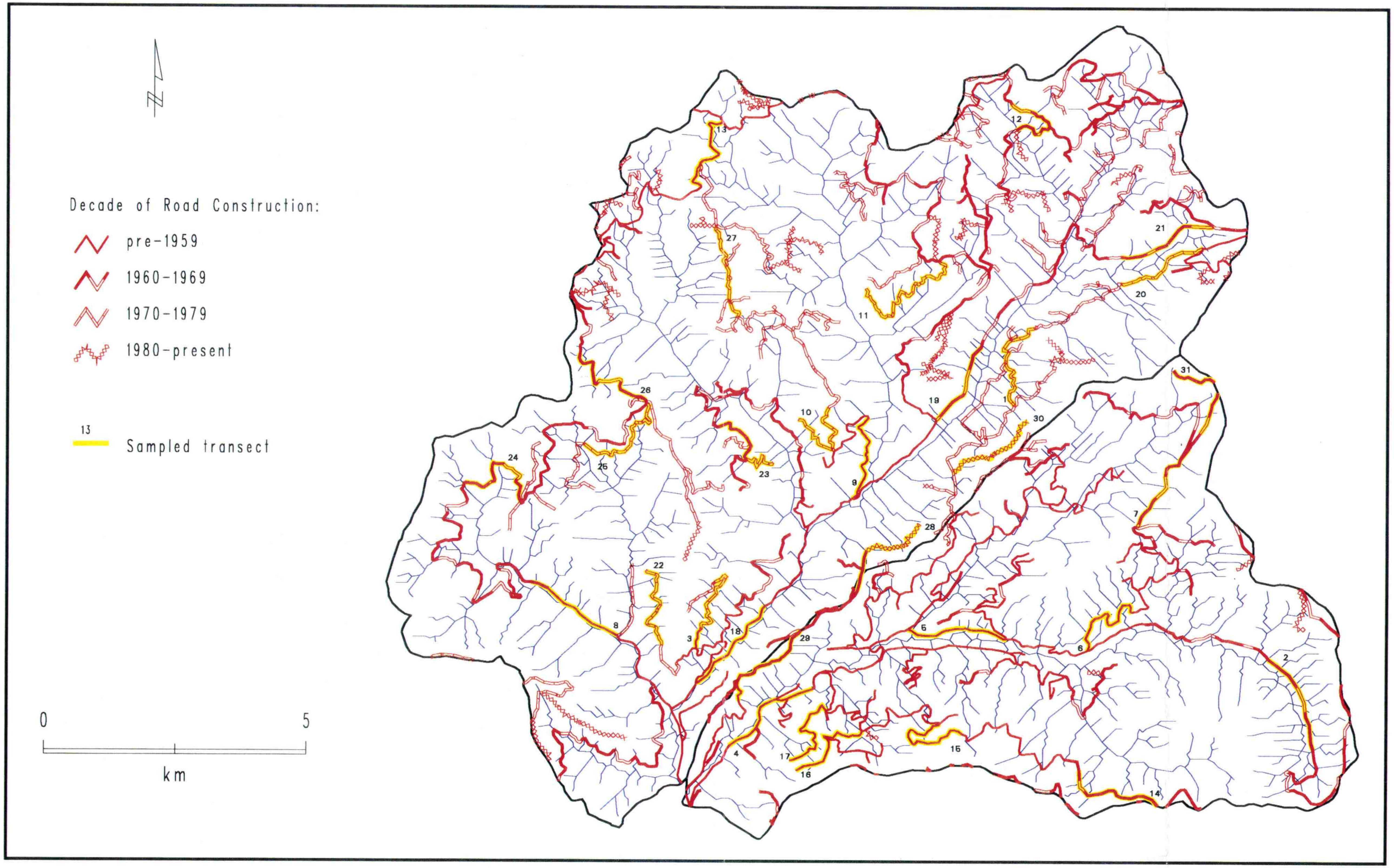
Table 4: Stratification of road network by decade of construction and hillslope position for transect sampling

	Lookout Creek					Blue River				
			No. transects sampled by hillslope position[b]					No. transects sampled by hillslope position[b]		
Constructed:	road length (km)	No. transects required[a]	valley bottom	midslope	ridge	road length (km)	No. transects required[a]	valley bottom	midslope	ridge
pre-1960	69.1	7	2	3	1	38.8	4	2	1	1
1960-69	45.2	5		2	3	78.3	8		5	1
1970-79	2.1	-				86.1	8		6	2
1980-present	2.1	-				27.2	3		1	1

[a] Number of 2-km transects required to achieve 20% sample of total road length constructed in each decade.

[b] Hillslope position refers to location of each sampled transect. Due to time constraints, total number of transects actually sampled was slightly less than number required to achieve 20% sample.

Figure 4: Road network and location of sampled transects



b. Pilot Study

A pilot study was conducted at the outset of field sampling to develop a methodology for the surveys. Four transects were initially selected for survey, according to the stratification scheme discussed above. The objective of this exercise was to develop a method for recording length between culverts and a culvert classification scheme relevant for the analysis of flow path modification by roads.

Upon evaluation of the pilot study results, the following sampling tactics were adopted:

(1) distance between culverts would be measured by automobile odometer, allowing coverage of the requisite number of transects within the time available;

(2) culvert outflows could be classified into one of three categories as described below;

(3) a subsample of the transects should be resampled during winter/spring runoff events to verify culvert classifications assigned during the summer field survey and to estimate the error associated with calculations of connected road length that were based upon the culvert classifications;

(4) the four transects sampled during the pilot study should either be replaced by four new transects for the final study or be resampled, since they were not consistently or reliably sampled. The latter option was chosen due to time constraints, and resurveys were conducted during the subsequent spring.

c. <u>Field Surveys</u>

The field survey was conducted from July to August 1992 to determine what fraction of the road network routed water to surface flowpaths. The following characteristics were recorded for each sampled road segment: length of road draining to a culvert, height of the cutbank, road grade, and routing of water below the culvert outlet. Measurements of road grade were made using a clinometer. Distances between culverts were estimated to the nearest 0.01 mile (0.02 km) by driving the transects in an automobile. While the auto odometer measures only to the 0.1 mile, comparison of driving measurements to measurements taken during the pilot study using a bicycle odometer with a 0.01 km measurement resolution indicated that we could interpret odometer measurements with an accuracy of 0.02 km. Average hillslope angle on which the road is located was extracted from the GIS, which generally underestimates local slope slightly, but provides a consistent means for characterizing average hillslope steepness along a transect.

To determine connectivity of road surfaces and ditches with the channel network, culvert outflows were classified in three categories: (1) those that delivered water directly to a natural stream channel, (2) those that delivered water onto a soil surface where reinfiltration occurs, or (3) those where water delivered by the culvert had incised a gully in the hillslope and evidence of a surface flowpath exists.

Presence of a pre-existing channel above and below the culvert was used to assign a culvert to category (1). In addition, on some road segments located approximately parallel to higher order stream channels, some ditch-relief culverts drained directly into the adjacent channel, and were also assigned to category (1). All remaining ditch-relief culverts were recorded either as returning water to subsurface flow where no evidence of an eroded flow path appeared below the culvert outlet, or as a newly-incised gully where evidence of erosion and formation of a channelized flow path existed for at least 10 meters below the culvert outlet.

d. Survey Verification

Eight of the originally surveyed 31 transects were randomly selected during the winter of 1993 to validate culvert outflow classifications assigned during the dry season. These re-surveys were conducted during rainfall events to verify that channelized surface flow was accumulating below culvert outflows classified as category (3) and to find evidence of infiltration or lack of channelized surface flow below culverts classified as category (2). In addition, hillslope seeps representing the emergence of subsurface flow along road cutbanks were noted.

The four transects surveyed during the pilot study were resurveyed during the winter. Data from this resurvey replaced data collected during the pilot study.

3. GIS Assessment of Network Extension Effects

Field data on the length of road connected to channelized flow paths were extrapolated to the entire study area using data derived from the GIS. The GIS was further used to estimate stream length during various runoff seasons, in order to evaluate the extent to which connected road segments modify drainage density.

Extended stream networks were simulated using a 30-meter digital elevation model and a flow routing algorithm available in the ARC/INFO geographic information system. In the algorithm, digital elevation data are conditioned in three phases to generate data sets of the topographic structure of the basins. The first step involves filling depressions on the DEM to remove anomalous data points. Next, a flow direction is calculated for each cell on the DEM grid. Flow directions can be to one of eight cells that surround any given cell. Finally, a flow accumulation map is constructed by calculating the total number of cells that drain into each cell of the DEM. The stream network is derived from the flow accumulation map by designating a minimum source area for channel initiation. Further details of the algorithm are provided in Jenson and Domingue (1988).

The algorithm was run a number of times, varying the threshold for channel maintenance, in order to estimate the extent of the stream network that would exist throughout the runoff season. Generated networks were validated against surveyed stream maps of the Lookout Creek basin and against stream-crossing locations recorded on roads surveyed for this study.

IV. RESULTS

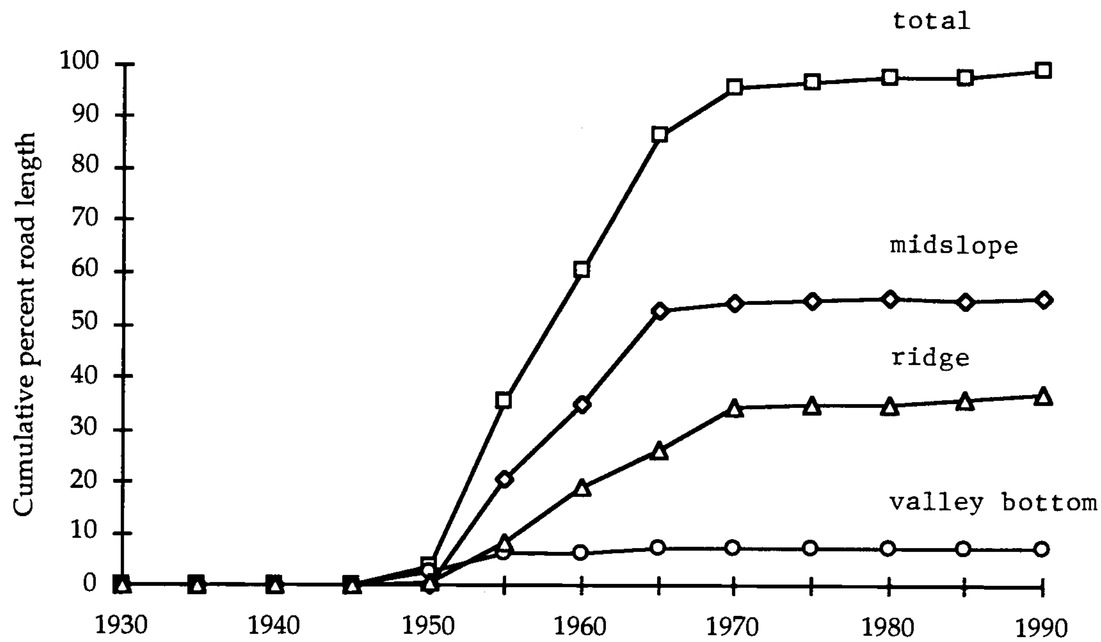
A. Historical Pattern of Road Development

Lookout Creek and Blue River road networks have similar distributions with respect to slope, elevation, and hillslope position (Figures 5 and 6). Lookout Creek has a larger portion of its road length (50%) below 800 m elevation than Blue River (30%) (Figure 6). This is partly explained by differences between the two basins in the distribution of basin area within elevation zones (Figure 7), but may also reflect changing road placement with time. The primary difference in road development between the two basins is the time of road construction (Figure 5). Both basins were entered prior to 1940, with a majority of the road construction activity occurring in Lookout Creek after 1950 and in Blue River after 1960. In both basins, road network growth proceeded from valley bottoms to ridgetops. As of 1993, road density in each basin was 1.9 km/km^2 (Table 3).

The temporal offset of road development in Lookout Creek, approximately one decade prior to that in Blue River, parallels observed changes in peak flows in these basins. Jones and Grant (in prep, b) found that unit area peak flows were higher in Lookout Creek than in Blue River during the 1950's and 1960's, when the cumulative area harvested and in roads was greater in Lookout Creek, and that Blue River experienced higher unit area peak flows after 1970, when the cumulative area harvested and in roads exceeded those in Lookout Creek.

Figure 5: Road development over time by hillslope position

(a) Lookout Creek



(b) Blue River

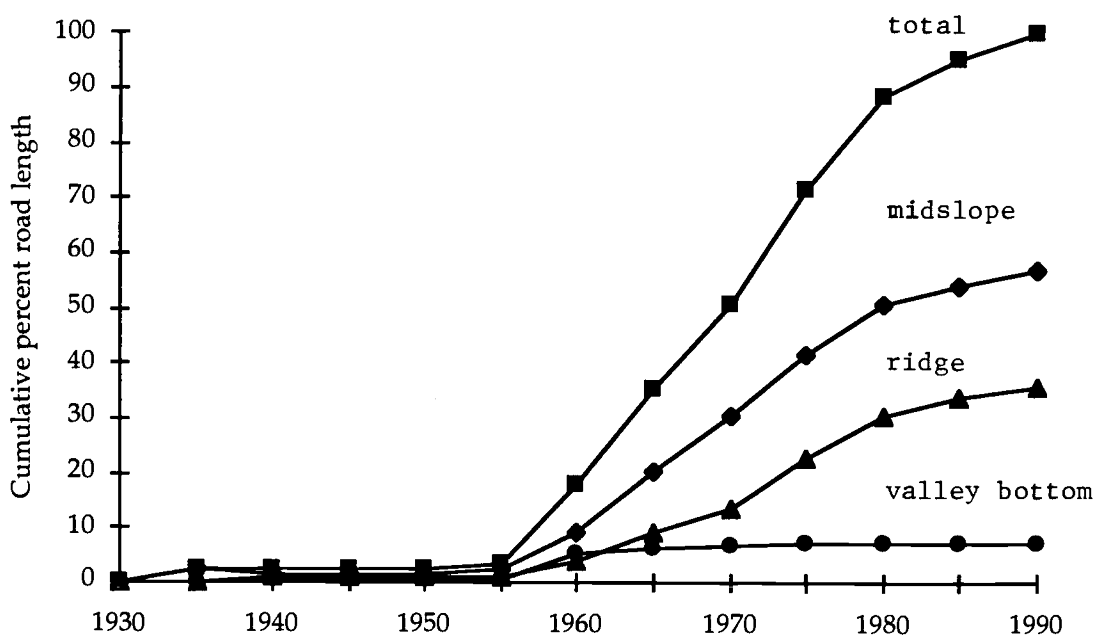
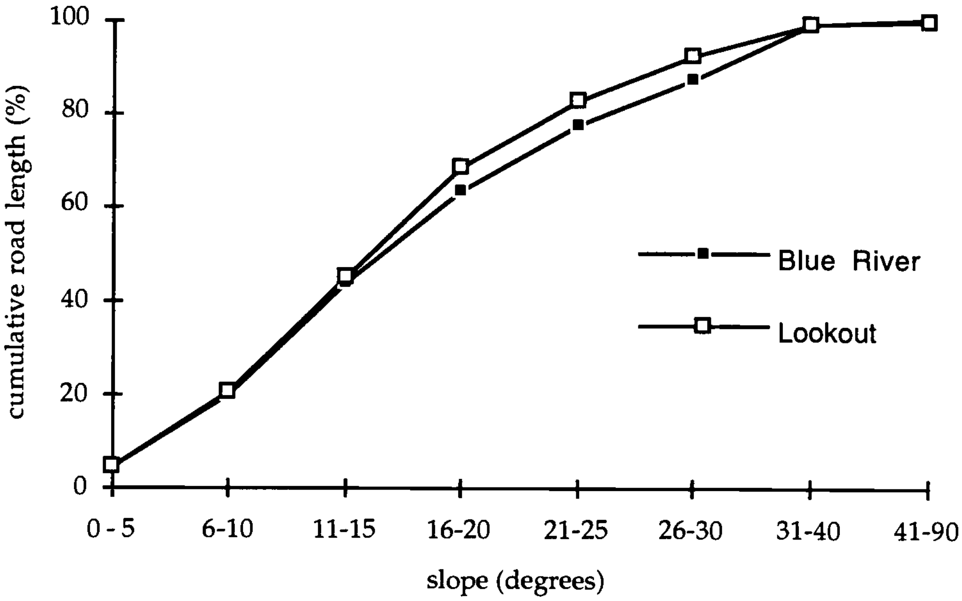


Figure 6: Road distribution by slope and elevation



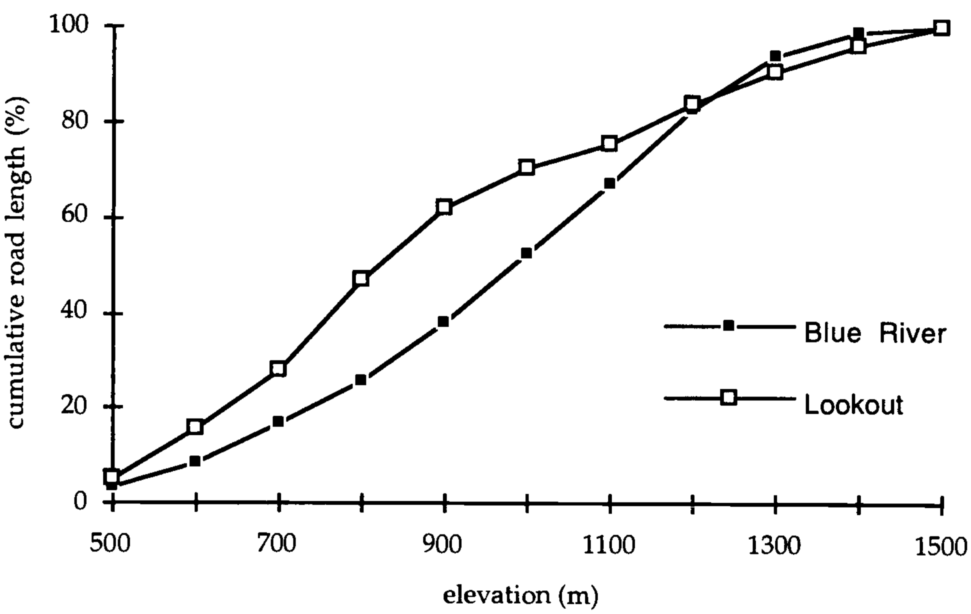
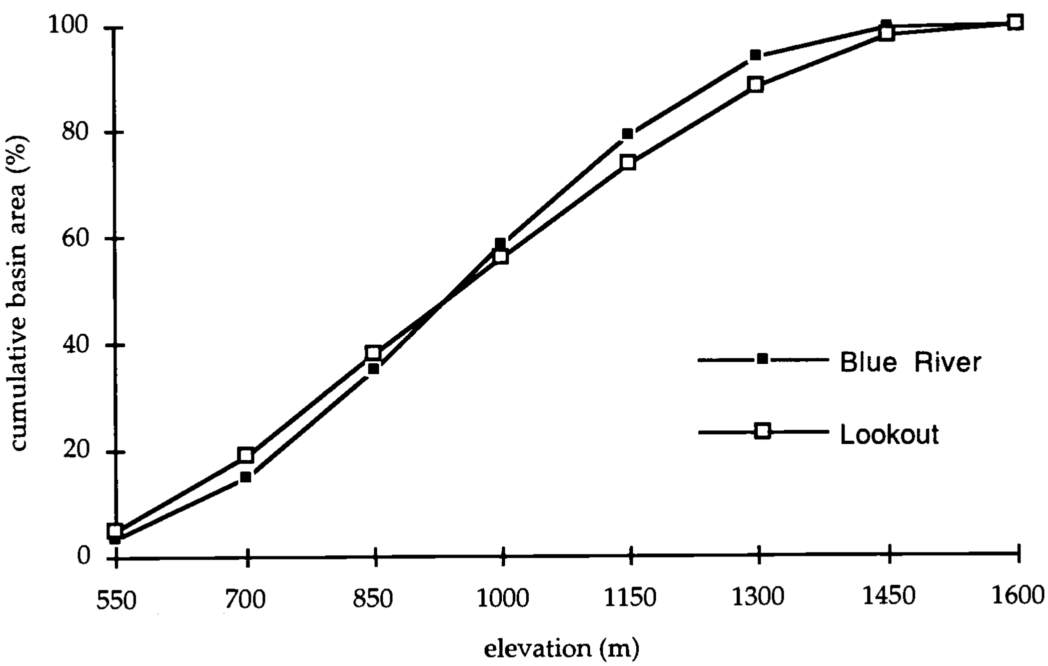


Figure 7: Distribution of basin area by elevation



B. Road Drainage Configuration

Sixty-two kilometers of road were surveyed for this research, and data were collected at 436 culverts (Table 5). One hundred and forty-five (33%) of these culverts were stream crossing culverts; the remaining 291 (67%) were ditch-relief culverts.

1. Stream Crossings

The number of stream crossing culverts ranged from 0 to 10 per 2-kilometer transect, with a mode of 4 to 5 crossings per transect. The average number of stream crossings was 2.3 per kilometer (Table 5). Midslope roads parallel to contours and perpendicular to gravitational flowpaths would be expected to have the highest frequency of stream crossings. Valley bottom roads are typically parallel to a higher-order stream channel, while ridgetop roads often occupy unchanneled portions of the landscape. In Lookout Creek and Blue River, where road construction proceeded from valley bottom to midslope to ridge, the frequency of stream crossings is highest on roads constructed in the 1950's and 1960's -- the early years of road construction in these basins. This trend is apparent both on roads sampled in the field (Figure 8) and in the declining frequency of stream crossings over time for the entire basins (Figure 9), as measured by a GIS overlay of the road network with the extended stream network (estimated by a 2-ha source area).

Table 5: Characteristics of the road drainage system

Culvert Type:	Stream-crossing	Ditch Relief			total / average
outlet discharge to:	stream	stream	gully	sub-surface flow	
No. of culverts surveyed	145	8	101	182	436
As % of total culverts surveyed	33	2	23	42	100
As % of ditch relief culverts	- -	3	35	63	100
No. / km.	2.3	0.1	1.6	2.9	7.0
Length of road routed to: (km)	19.8		13.7	24.7	58.2
Avg. % road length routed to:	33.8	- -	23.5	42.7	100
Standard deviation	18.9	- -	13.3	19.7	- -
Avg % road length routed to surface flowpaths (e.g. streams & gullies)	- -	- -	- -	- -	57.3

Figure 8: Distribution of stream crossings by decade of road construction for 2-kilometer surveyed transects

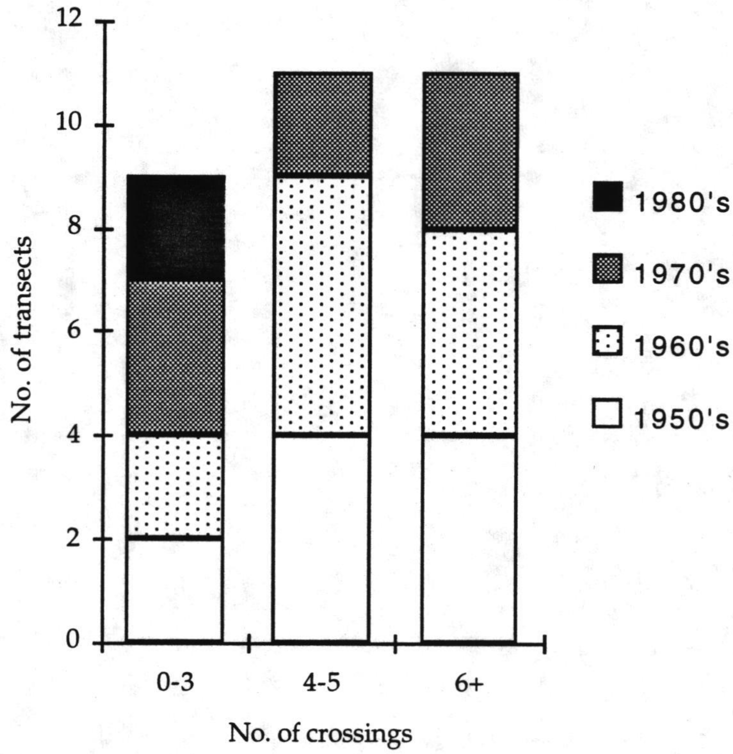
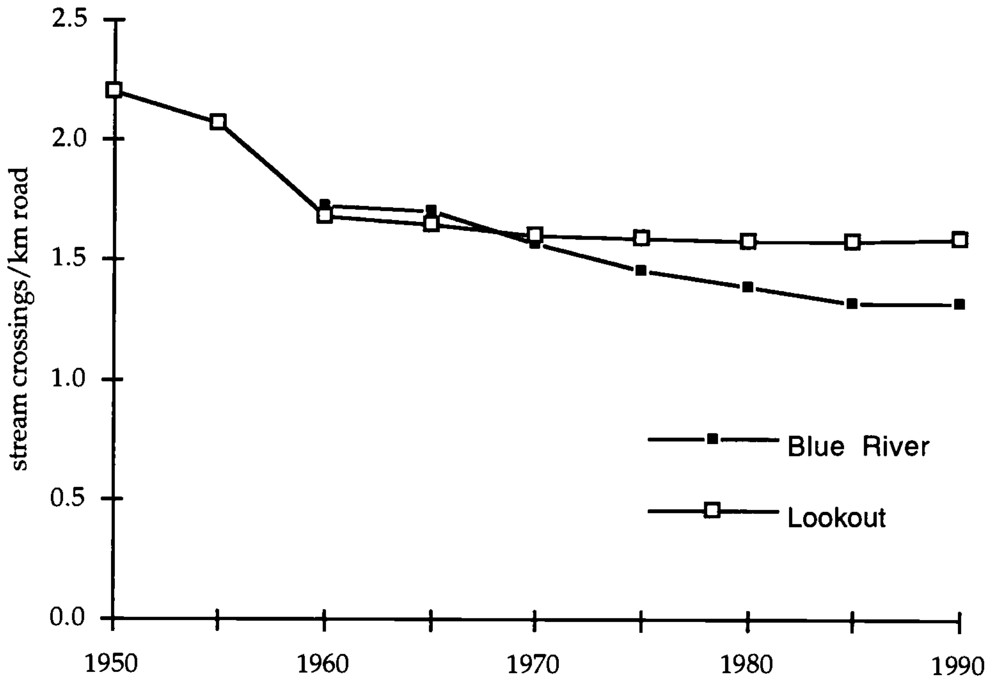


Figure 9: Stream crossings per kilometer of road for entire basins*



* calculated on a cumulative basis over time

Note: 1960 start date for Blue River corresponds with period of active road construction

2. Ditch-relief Culverts

Ditch-relief culverts were examined to determine the routing of water below culvert outlets. Of the 291 ditch-relief culverts examined, 182 (63%) discharged outflow onto unchanneled hillslopes where infiltration occurs. Gully erosion on hillslopes below culvert outlets was evident at 101 (35%) of the ditch-relief culverts examined (Table 5).

To determine whether observed gullying could be explained using measurements available from the field survey and the GIS, data for the ditch relief culverts were analyzed by multiple logistic regression (Tabachnick and Fidell, 1989). Variables analyzed were (1) culvert spacing, measured in the field as the length of road draining to each culvert, (2) road grade for the portion of road draining to each culvert (also measured in the field), and (3) hillslope steepness on which the road segment draining to each culvert is located, determined from GIS data. Interaction terms were used to describe how two variables jointly determine the mean response. Culvert spacing and road grade were continuous variables; hillslope angle was a categorical variable equal to zero for slopes less than 40% and one for slopes equal to or greater than 40%.

The statistical model indicated that there is no association between gullying and culvert spacing, or road grade, or an interaction between these variables ($X^2 = 3.48$ with 3 degrees of freedom; $p < 0.32$). Addition of the hillslope steepness variable to the statistical model shows a statistically significant association with observed gullying ($X^2 = 20.35$ with 1 degree of freedom; $p < 0.00001$). There appears to be some interaction between hillslope steepness and both culvert spacing and road grade ($X^2 = 8.68$ with 2 degrees of freedom; $p < 0.01$). Road grade, however, is only weakly associated with gullying. Culvert spacing, hillslope steepness, and an interaction between these two terms provide the best predictive model of the incidence of gullying for this data set ($X^2 = 29.29$ with 4 degrees of freedom; $p < 0.00001$). The interaction between slope steepness and spacing indicates that the effect of culvert spacing on gullying is different for slopes greater than 40% than for lesser slopes. Increased spacing may result in increased incidence of gullying for steep slopes (e.g. ≥ 40%), but spacing may have little effect on gullying on gentle slopes.

The results of this statistical analysis indicate that gullying below ditch-relief culverts can be predicted with some confidence for the population of Lookout Creek and Blue River roads. Hillslopes equal to or greater than 40% in this study area have the highest probability of gullying.

The degree to which this statistical model accurately predicts the occurrence of gullying as measured in the field can be assessed with an incidence matrix (Table 6). Observed gullying was tabulated against incidence of gullying predicted by the statistical model that includes spacing, hillslope steepness and an interaction between spacing and hillslopes. This model accurately predicted observed occurrence of gullying and no gullying in 184 of the 275 cases (e.g. for 67% of the cases).

Table 6: Incidence matrix for comparison of observed gullying against occurrence predicted by statistical model.

		Predicted		
		gully	no gully	totals
Observed	gully	58	45	103
	no gully	46	126	172
	totals	104	171	275 *

* Eight (8) culverts omitted from analysis due to insufficient data on slope and road grade.

3. Connectivity of the Road and Stream Networks

The length of road ditch draining to each culvert was measured to assess the connectivity of the road network with stream channels. For the 31 sampled road segments, the average percent of road length routed to natural channels is 33.8% (standard deviation 18.9%) (Table 5).

Portions of the road network that discharge road runoff to ditch-relief culverts where gully erosion has occurred also represent a potential extension of the drainage network. These gullies deliver road runoff over rapid surface flowpaths directly into nearby streams or to downslope areas of the basin where reinfiltration and eventual concentration in a stream channel will occur. Of the 31 sampled transects, 23.5% (standard deviation 13.3%) of the road length, on average, routed road runoff into gullies below ditch relief culverts (Table 5).

The measured lengths of road ditch draining to each culvert combined with the culvert discharge classifications indicate that 57.3% of the road length surveyed drains to a channelized surface flowpath (e.g. a natural channel or newly-incised gully) (Table 5). In short, roads with inboard ditches in this study area create a set of additional surface flowpaths, hydrologically integrated into the stream network, that is equivalent to almost 60% of the total road length.

C. Extended Stream Network Simulation

Stream networks expand and contract dynamically in response to moisture conditions in the basin. The potential impact of roads in extending drainage density thus depends upon the length of road connected to the channel system relative to the length of the stream network, which was measured in

Lookout Creek and Blue River from: (1) a stream network for basins of 100 ha or greater based on USFS primary base series 1:24,000 quadrangles (G. Lienkaemper, GIS Director, Corvallis Forestry Sciences Laboratory, Corvallis, OR, personal communication), (2) a map of the perennial and intermittent stream network approximating late-winter (or early spring) base flow in Lookout Creek compiled by field survey (Lienkaemper, 1977), and (3 and 4) two simulated channel networks initiating from a constant source area of 10 ha and 2 ha, using the algorithm for drainage delineation on a DEM (Arc/Info, Grid module, ESRI).

The four map sources (Figure 10) produced quite different estimates of stream length (Table 7). The summer low flow network may be best represented by the map of streams draining basins ≥ 100 ha (Figure 10a). Lienkaemper's map of the Lookout Creek stream network (Figure 10b), surveyed in the spring of 1977, includes perennial and intermittent streams. It closely matches the stream length derived from the DEM using a 10-ha source area for channel initiation. This stream network based on a 10-ha source area (Figure 10c) was therefore used to approximate the winter baseflow network. Based on field observations of channels in the study basins during winter runoff events (Swanson, personal communication), a 2-ha source area for channel initiation was used to approximate stream length during high-flow winter runoff events (Figure 10d).

Stream length is very sensitive to estimated source area. Total stream length increases by 35% for Lookout Creek and by 39% for Blue River as the source area is decreased from 10 ha to 2 ha (Table 7). Growth in the length of first-order channels is dramatic as the source area necessary to maintain a channel decreases.

Two independent exercises were conducted to assess the validity of the simulated stream networks. The simulated 10-ha network was compared to Lienkaemper's (1977) surveyed map of Lookout Creek. The simulated map

Figure 10: Stream Networks

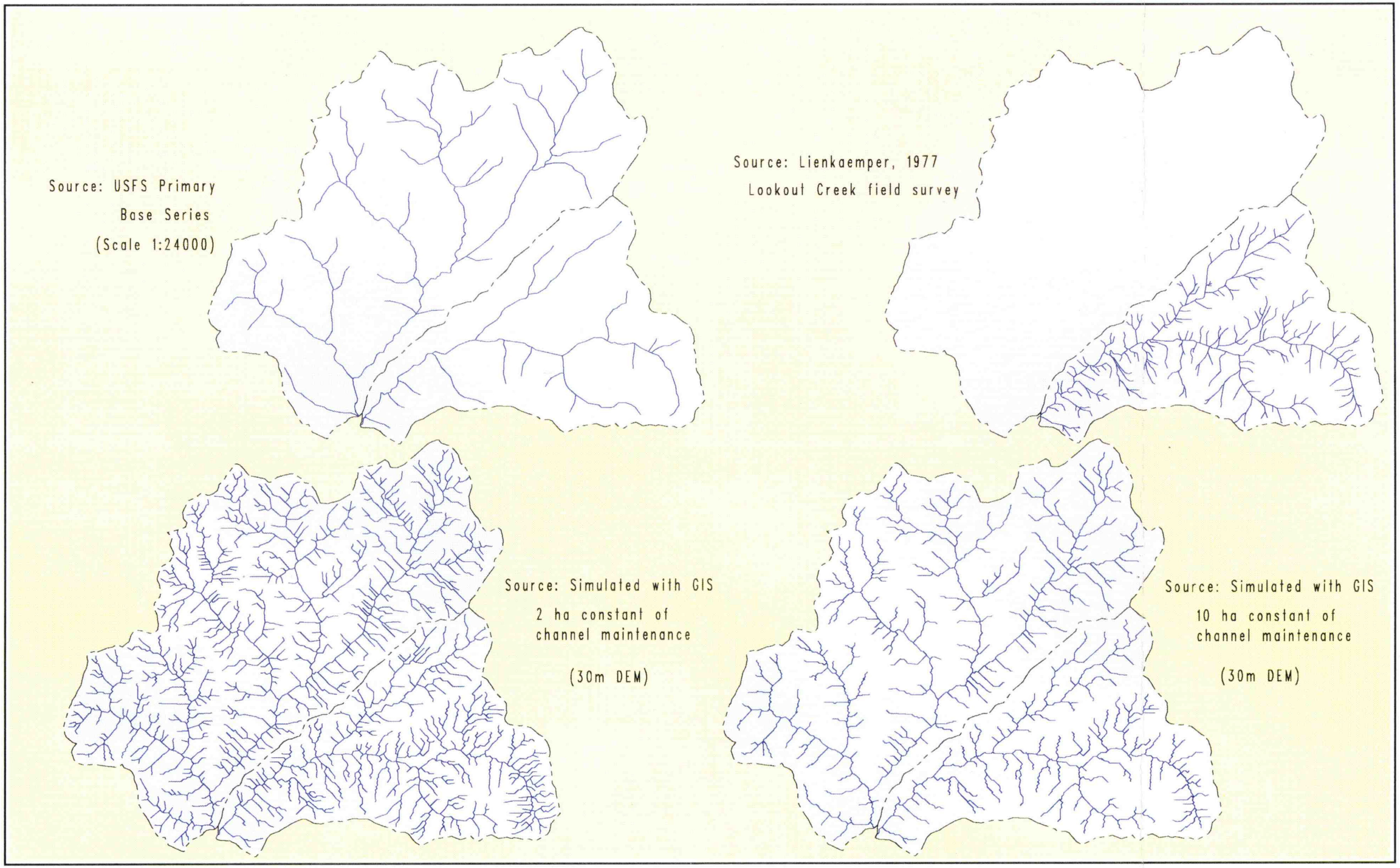


Table 7: Stream length (km) measured on available map sources

	Lookout Creek		Blue River	
	1st order	total network	1st order	total network
Map source:				
USFS Primary Base Series	28	46	50	95
Lienkaemper, 1977 field survey	83	138	--	--
Simulated 10 ha source area	73	122	118	208
Simulated 2 ha source area	118	189	205	341

based on a 10-ha channel source area produced a stream length of 122 km, only 11.6% less than the 138 km mapped by Lienkaemper (Table 7). Second, the simulated network based on a 2-ha source area was validated by comparing predicted to observed stream crossings along surveyed road transects (Table 8). Observed stream crossings were adjusted to account for streams occurring along a transect within 30m of an adjacent stream, which is below the resolution of the 30 meter DEM used to produce the simulated stream network. After accounting for the constraints of the DEM resolution, the simulated map correctly predicted the number of stream crossings (±1) detected in the field for 17 of 31 transects. Transects where the simulation over- and under-predicted stream crossings by 2 or 3 were evenly distributed. This validation suggests that the map has some positional errors but overall does a good job of representing the extended drainage network.

D. Drainage Network Effects

Field results of this study indicated that approximately 57% of the road length in Lookout Creek and Blue River is connected to natural channels or gullies, thereby discharging road runoff into surface drainage courses. The temporal changes in the length of road routed to the three outlets shows a trend toward an increasing proportion of the road network routed to subsurface flow over time, and a decreasing proportion of the road network routed to stream channels (Figure 11). The proportion of the road length routed to gullies has remained relatively constant over the two to four decades during which road construction has taken place in Lookout Creek and Blue River. This suggests that as road construction has moved up hillslopes, the connectivity of roads to stream

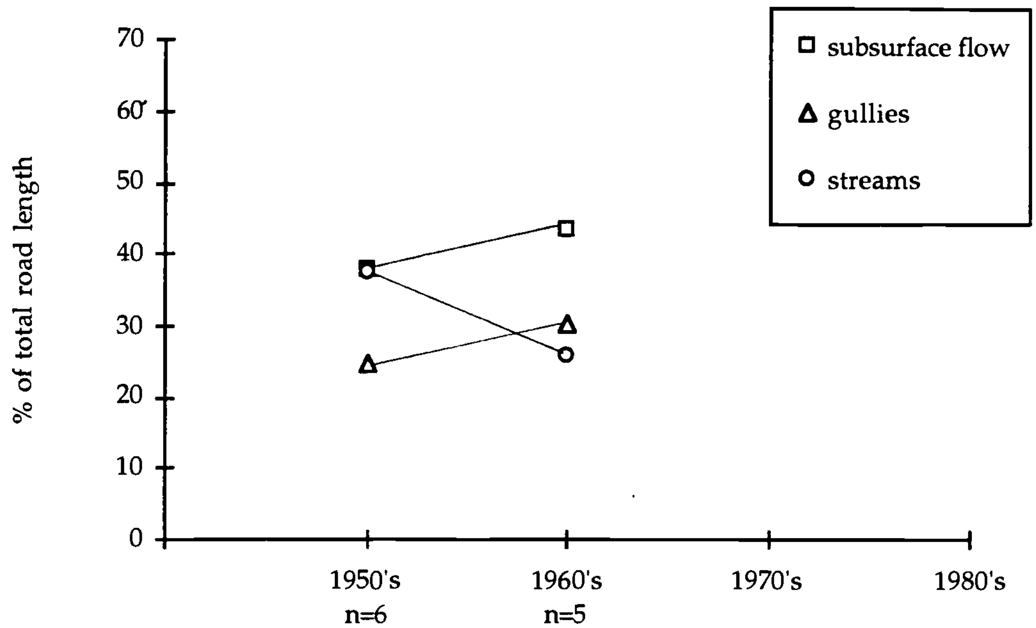
Table 8: Contingency table of stream crossings by roads for 31 2-km transects

Stream Crossings predicted by map [b] \ Stream Crossings dectected on field surveys [a]	0	1	2	3	4	5	6	7	8	9	10
0											
1	27					29					
2			17	30	31		10				
3		28		16	7	23		9			
4			22	21	14, 15 20, 24, 26	11					
5				5, 25			6				
6			19		8	13					3
7						1		4	2, 12	18	
8											
9											
10											

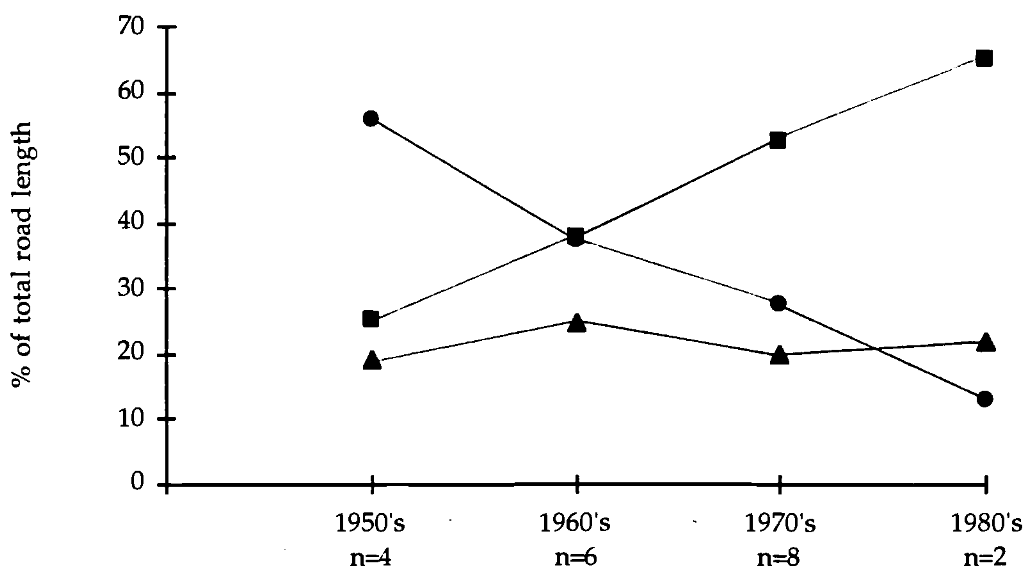
[a] Adjusted for DEM resolution (e.g. stream crossings with 30m of adjacent stream crossing counted as one)
[b] Using map overlay of roads and 2 ha simulated stream network

Figure 11: Temporal trends in routing of ditchflow for Lookout Creek and Blue River roads. (Number of transects used to summarize trend is given below each decade).

(a) Lookout Creek



(b) Blue River



crossings has decreased. However, the constant proportion of gullying over time suggests that these roads still have the potential to become integrated into the stream network through the formation of gullies and new channels below culvert outlets. The rate at which this connectivity takes place is unknown and may increase if roads are not maintained.

The impact of these integrated road segments on the stream network may be measured in terms of changes in drainage density. Using the stream networks simulated for this study, roads in Lookout Creek and Blue River may increase drainage density by as much as 36% to more than 60% (Table 9). In summary, the impact of roads in extending drainage density varies as the stream network expands and contracts throughout the year.

E. Assessment of Error

Error in the results reported for this study comes from two sources: field classification of culvert outflows from surveys conducted during the summer, and estimated length of the extended drainage network. Estimates of the error associated with these sources is discussed below.

1. Field Classification of Culvert Outflows

To assess the reliability of outflow classifications for ditch-relief culverts, eight transects were randomly selected for resurvey during the winter of 1992-93. Stream crossings were readily apparent at this time, and were re-counted to determine frequency. Ditch-relief culverts were re-examined during storm events to determine whether culvert outflow reinfiltrated or traveled as surface

Table 9: Stream length, drainage density and changes with integrated road network.

	Lookout Creek	Blue River
1. Stream length (km)		
a. estimated winter baseflow network, simulated with GIS - 10 ha-source area	122	208
b. estimated winter high-flow network, simulated with GIS - 2 ha-source area	189	341
2. Drainage density (km/km^2)		
a. estimated winter baseflow network	2.0	1.7
b. estimated winter high-flow network	3.0	2.9
3. Road length connected to surface flowpaths[a] (km)	68	132
4. Effective drainage length [b] (km)		
a. estimated winter baseflow network	190	340
b. estimated winter high-flow network	257	473
5. Modified[c] drainage density (km/km^2)		
a. estimated winter baseflow network	3.1	2.9
b. estimated winter high-flow network	4.1	4.0
6. Change in drainage density (%)		
a. estimated winter baseflow network	56	63
b. estimated winter high-flow network	36	39

[a] assumed to be 57.3% of total road length, based on field survey results
[b] includes streams and connected road length
[c] reflects addition of connected road length

runoff in gullies for a minimum of 10 meters. Comparison of the original survey results to results compiled after resurveying transects indicated an average error of ± 4.6% for stream crossings, ± 5.6% for ditch-relief culverts discharging to gullies, and ± 7.1% for ditch-relief culverts discharging onto hillslopes where reinfiltration occurs.

2. Estimation of Drainage Network Length

Error associated with the drainage network estimation is more difficult to assess. Two probable sources of error may have compensating effects. The digital elevation data used to simulate the extended stream network have a pixel resolution of 30 meters. Occurrence of two or more streams within a 30 meter pixel is beyond the resolution detectable on a DEM. In computing the contingencies shown in Table 8, frequency of stream crossings along sampled transects was slightly higher than those indicated by the simulated stream network on several transects. Inability of the DEM to adequately capture the density of small streams leads to lower estimates than the actual maximum stream length. Conversely, designation of a two hectare threshold for channel initiation may overestimate the stream length in some parts of the basins and for some storm events. While a quantitative assessment of error for the extended stream length estimate is not possible, the probable sources of error may balance each other. In any case, the length of the stream network was used here only as a reference point from which to assess the relative increase in drainage density associated with roads.

VI. DISCUSSION

The results of this study indicate that (1) roads function as surface flowpaths to channel appreciable volumes of runoff, (2) a substantial portion of the road network in this study area is hydrologically integrated into the stream network, and (3) a number of factors that influence the magnitude of road impacts on streamflow can be identified.

A. The Role of Roads as Surface Water Channels

Three types of channels that differ in morphology and function can be identified in a roaded basin: roadside ditches, gullies incised below culvert outlets, and natural streams. Comparison of small, first-order channels to channels imposed by the road network reveals evidence of the hydrologic role of roads (Table 10).

The accumulation of runoff in mountain streams is thought to occur primarily through the mechanism of translatory flow (Hewlett and Hibbert, 1967). The primary source of runoff to roads, however, is intercepted precipitation from the road surface, and in turn this water is the primary source of runoff to gullies. When roads intercept subsurface water and when gullies are formed in local topographic depressions, they may also accumulate subsurface water by a similar translatory flow mechanism. The near perpendicular orientation of road ditches to subsurface flowpaths suggests that ditches may be particularly effective in capturing subsurface water when pore water pressures are sufficient to result in seepage (Nulsen, 1985). Subsurface flow seepage was observed on several road cutbanks in Lookout Creek and Blue River immediately

Table 10: Comparison of the morphology and hydrologic function of various channel types

	Channel type		
	natural, 1st order channels	roadside ditches	gullies
hillslope orientation	acute angles to gravitational flowpaths on hillslopes	perpendicular to subsurface flowpaths; parallel to higher order stream channels in valley bottoms; generally perpendicular to 1st order streams	parallel to gravitational flowpaths or at acute angles to gravitational flowpaths when gullies form in micro- topo-graphic depressions
accumulation of runoff	accumulate subsurface water by translatory flow or through macropores	intercept rainfall on area compacted by road surface; may also capture subsurface flow along cutbanks	transmit ditchflow downslope; may accumulate additional subsurface flow when gullies are formed in micro-topographic depressions
gradient	occur on slopes up to 80% in these study basins	range from 0% to 15%, averaging 7-8% for roads sampled in this study; may be as high as 30% for steepest roads constructed in PNW forests	can occur on slopes up to 100%
age	10^2 - 10^6 years	years to decades	years to decades
persistence of surface runoff	expand and contract throughout the water year according to the variable source area required for channel maintenance	respond to storm events, persisting from hours to days; may persist longer when the cutbank captures subsurface flow	sporadic; respond to runoff channeled through road ditches

following storm events in the winter of 1993. Roads and gullies would be expected to function as ephemeral streams, channeling water during and immediately after storms. However, to the extent that they capture subsurface flow, road ditches and gullies may persist as channels for long time periods following a storm event.

Age is another key difference between natural channels and channels formed by roads. While natural channels are the product of fluvial processes operating in drainage basins over time scales of hundreds to millions of years, channels formed by roads have existed only as long as the road, i.e. years to decades. Leopold et al (1964) discuss drainage basin evolution, indicating that the evolution of a drainage network may be modified by natural events or by landuse change. However, drainage networks may rapidly adjust to environmental conditions, such as catastrophic storm events or in response to landuse activity (Leopold et al, 1964; Dunne and Leopold, 1978). This research indicates that although natural stream networks are a product of long-term drainage basin evolution, they can be extended or modified over short time scales, e.g. in response to human landuse such as road construction.

Despite their differences from natural channels, ditches and gullies can channel appreciable volumes of water. Two discharge measurements taken in ditches during and immediately following storms were in the range of 1 to 7 L/sec (Appendix 3). These estimates are within the range of discharge measurements taken at culvert outlets by Reid (1981), where peak discharges from culverts were 0.3 to 12 L/sec.

In order to adequately assess the hydrologic effects of roads in forested basins, further research is needed to quantify the channel characteristics of roadside ditches and gullies. Field estimates of volumes, velocities, and time to concentration of road-related runoff must be obtained.

B. Integration of Road and Stream Networks

Estimating the integration of road segments into the stream network requires consideration of the many fates of road runoff on slopes below roads (Figure 12). Where road runoff is deposited onto hillslopes and infiltration occurs (Figure 12a), the drainage network is not substantially altered. Road lengths delivering water directly to stream channels (Figure 12b) are integrated into the stream network by design, extending the paths of surface runoff along the length of contributing road. Road segments delivering runoff to streams through channels formed by gully erosion (Figure 12c and 12d) are somewhat more complex, since the extent of their integration may depend upon a number of factors.

1. Gully Formation on Hillslopes Below Culverts

On hillslopes examined for this study, any eroded, channelized flowpath extending for at least 10 m below a ditch-relief culvert was classed as a gully. This classification actually encompasses several possible features, ranging from discontinuous gullies to debris-slide scars. The formation of a gully below a culvert outlet is significant in this study because it indicates a road-related extension of a surface flowpath that would not exist without the road. Several factors may influence the formation of gullies (Table 11). These factors may be characterized as those that relate to the force of water exerted on hillslopes and those related to the sensitivity of the site to the concentration of water and erosion of the soil mantle.

Figure 12: Road drainage and integration of roads and streams. Road runoff may discharge (a) to a ditch-relief culvert and infiltrate below outlet, (b) to a stream crossing culvert, (c) to a gully that extends some distance downslope, or (d) to a gully that connects to a stream channel or saturated zone near the channel.

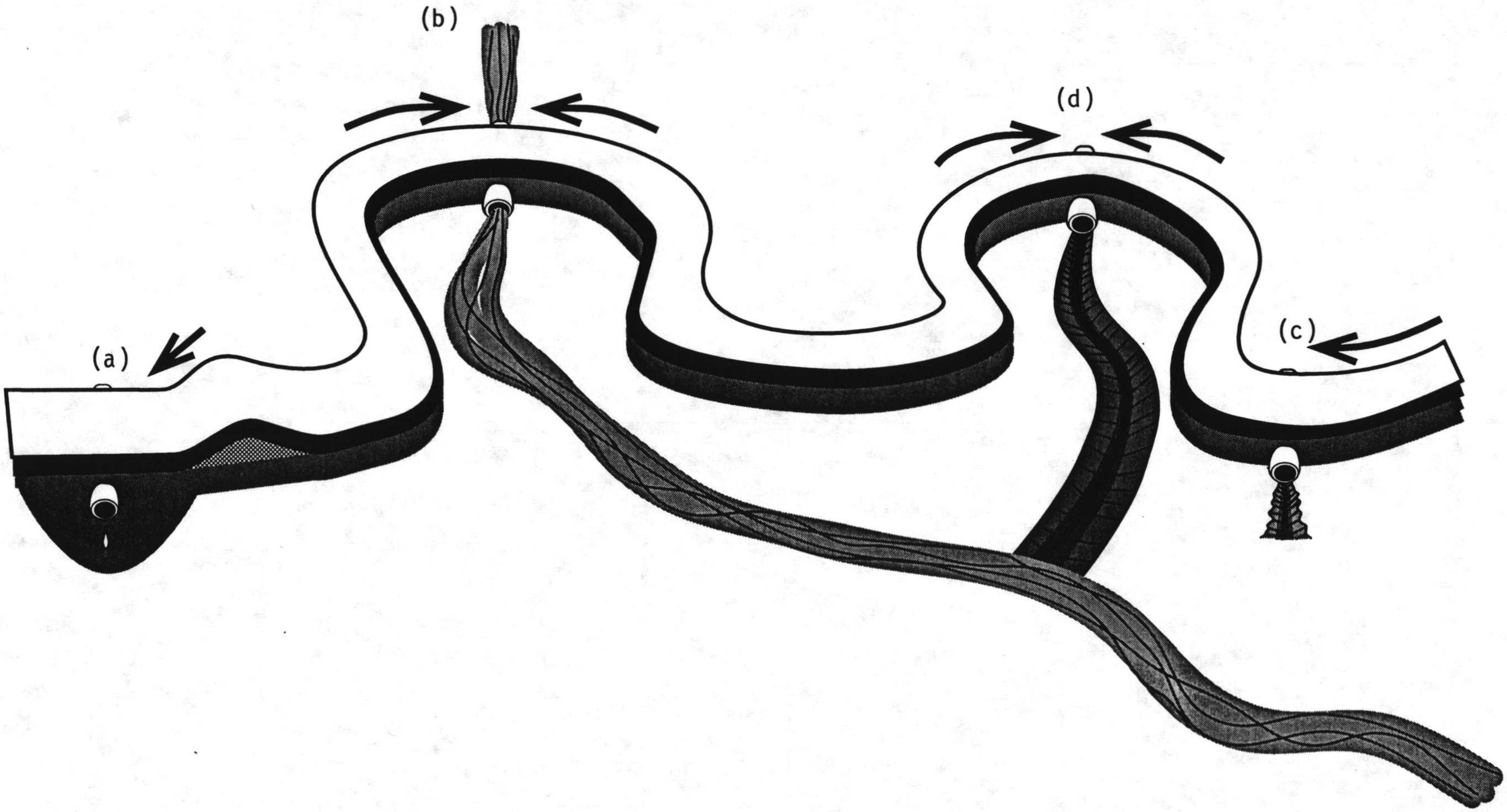


Table 11: Factors influencing formation of gullies below culvert outlets

Factors:	Discussion:
Force-related:	
• Discharge - volume of surface and subsurface flow intercepted by road	Erosive capacity of water expected to be directly related to volume discharged through culvert. Volume of discharge will increase with increasing culvert spacing or when substantial subsurface flow is intercepted at the cutbank.
- velocity of flow	Greater shear stress exerted as velocity of flow increases. Velocity of flow expected to increase as road grade increases.
• Plunge Height	Scour potential expected to increase with increasing plunge height of culvert above hillslope.
Sensitivity-related:	
• Soil Type	Likelihood of subsurface flow interception expected to be greater on colluvial soils than on more porous volcanic rocks with higher infiltration capacities.
• Depth to Bedrock	Likelihood of subsurface flow interception at cutbank expected to be inversely related to depth to bedrock. Efficiency of the road in capturing subsurface flow greatest when roadcut intersects bedrock.
• Slope Steepness	Moderately steep slopes (≈ 40-80%) expected to be most susceptible to erosion due to lower shear strength of steep slopes and velocity of outflow as it moves down slope. (Extremely steep slopes > 80% may have plunge heights significantly long to constrain detection of gullies).
• Concavity	Outflow discharged onto topographic concavity adds additional volume of water to zone of subsurface flow convergence. Increased likelihood that saturated conditions will be met and overland flow will occur.
• Vegetation	Susceptibility of hillslope to gully erosion expected to be inversely related to vegetative cover (including the root system) that serves to add shear strength to soil layer.

The statistical analysis of gullying below culvert outlets showed that the probability of gullying was significantly positively related to culvert spacing and hillslope steepness but not to road grade. Increased spacing between culverts increases the volume of discharge routed along the ditch and through the culvert, thereby increasing the force of scour on the hillslope. The impact of increased culvert spacing on gullying is corroborated by the findings of Piehl (1987). While increased road gradient will increase the velocity of ditchflow, and might be expected to increase erosion on hillslopes below culvert outlets, the data collected for this study indicated only a weak association between road grade and gullying. Hillslope steepness, however, appeared to have a substantial effect on gully formation. Slopes equal to or steeper than 40% had a significantly higher occurrence of gullying than lesser slopes. Steeper slopes would be expected to have lower shear strengths and therefore be more susceptible to erosion. In addition, the plunge height, or distance from the culvert outlet to the ground surface, may increase on steeper slopes, causing greater scour as culvert outflow contacts the ground surface. Engineering analyses of the impact of culvert slope, plunge height and other design factors on gullying were beyond the scope of this study, but have been investigated elsewhere (Piehl, 1987; Piehl et al, 1988).

Additional factors expected to affect the formation of gullies below culvert outlets include soil type, depth to bedrock, and topographic shape of the hillslopes (e.g. concavity, convexity, or planar form) since these variables should influence the capture of subsurface flow on road cutbanks. Finally, vegetation cover and associated root strength would be expected to increase slope stability and decrease the likelihood of gully formation.

2. Connectivity of Gullies to Stream Channels

Because gullies observed in this study concentrated surface runoff for some distance downslope, they were considered to be important surface flowpaths. The role of gullies in extending the drainage network depends upon the connectivity to natural stream channels, which may vary as the extent of the channel network changes. In some instances, gullies may terminate after short distances, allowing channeled flow to infiltrate (Figure 12c). In other instances, gullies may be fully connected to nearby stream channels, discharging road-generated runoff into the channel (Figure 12d). Gully connection to a stream channel may be achieved when flow is deposited into topographic depressions or seasonally-saturated zones that become part of the channel network under certain, high runoff events. During high runoff events in the winter of 1993, for example, several gullies observed in watershed 3 of Lookout Creek discharged onto saturated areas which were slightly upslope of well defined channels. For these reasons, the length from gully head to stream channel is difficult to measure, since it is inversely related to stream network extension in some instances and may not be a static length.

3. Debris-slide Sites and Relationship to Gullies

Some of the sites classified as gullies in this study appeared to have experienced initial disturbance by road-fill failures, resulting in debris slides that strip the soil mantle below the road, possibly extending downslope to the channel. Such sites are particularly susceptible to gully development if some soil or subsoil remains for channel development. Although observation of road-related landslides was not included in the study design, comparison of mapped debris-slide sites in the Lookout Creek basin with gullies noted in the field surveys showed some co-occurrence of gullies and debris slides. On the 22 km of road surveyed in Lookout Creek, 43 culverts exhibiting gully erosion were found. There are 17 inventoried, road-related debris-slide sites on these road segments (Swanson and Dyrness, 1975; Swanson, unpublished data). Comparison of debris-slide sites to surveyed gullies indicated that 10 of the 17 debris-slide sites (59%) were classified as gullies in this study. Four of the remaining sites were classed as a channel in this study, and three could not be adequately correlated to surveyed sites without further field investigations.

On the 119 km of road in Lookout Creek, 70 road-related debris slides have been inventoried (Swanson and Dyrness, 1975; Swanson, unpublished data). Based on the survey average of 1.6 culverts per road kilometer exhibiting gully erosion (Table 5), the estimated number of road-related gullies in Lookout Creek is 190. If 59% of the 70 debris slides correspond to these gullies, approximately 41 of the road-related gullies may have been initiated by debris slides. In short, slightly more than 20% (41/190) of the road-related gullies may have been initiated by debris slides. This estimate, however, is based upon extrapolation of study results to the entire Lookout Creek basin, without careful field examination of debris-slide sites. This issue, which arose late in the study, has underscored the need to further examine the integration of segments of the road network to stream channels via debris-slide tracks. Based upon these correlations of surveyed gullies to inventoried debris slides, however, it is evident that surface flowpaths below road drainage structures develop from two sources: fluvially-eroded gullies formed at the culvert outlet and tracks of debris slides from roads which may then be gullied by water from culvert outlets. The impact of these flowpaths on extending the drainage network requires additional study.

C. Factors Influencing the Magnitude of Road Effects

Integrated road segments have the potential to enhance routing efficiency during and following storms, when roads function as surface flowpaths, extending the stream network and increasing drainage density. The magnitude of the effect of this integrated road network on hydrologic response, particularly on the generation of peak flows, depends upon a number of factors including (1) road design, (2) hillslope position of the road, (3) road age, (4) seasonal soil saturation, (5) geologic substrate, and (6) climatic regime.

1. Road Design

Several aspects of road design play a role in the extent to which roads may alter peak flow generation. Cut and fill roads typically have a wider impermeable road bed than endhaul roads. Surface design (e.g. insloped, crowned or outsloped) controls the contribution of runoff to a ditch or to hillslopes. Surfacing material used in construction may impede infiltration on the road surface. Soil type, particularly the presence of highly aggregated soil particles which would be expected to enhance infiltration, may also impact the magnitude of road-surface runoff. Decaying organic matter in the road fill may provide subsurface macropores and the opportunity for greater infiltration of water in the ditch. These factors control the concentration of surface runoff, but culvert design, spacing, and placement will control the extent to which road runoff is contributed to streams. In this study, road design was considered only in terms of evolution in culvert spacing and hillslope position. Other aspects of road design detailed above will control the volume of runoff generated on roads and the extent to which roads alter natural hydrologic flowpaths.

2. Hillslope Position

The hillslope position of a road affects both the volume and timing of water delivery to channels (Table 12). Water contributed to the mainstem channel by a valley-bottom road will be rapidly delivered to the basin outlet, but the volume of runoff contributed by valley-bottom roads may be small relative to runoff volume from roads in other hillslope positions. In contrast, midslope roads may generate greater volumes of surface runoff when subsurface flow is intercepted. Delivery time to the basin outlet, however, is relatively slower than that of valley bottom roads. Ridgetop roads intercept little subsurface flow, but may concentrate sufficient volumes of water to initiate new channels on previously unchanneled hillslopes (Montgomery, in prep), resulting in more rapid routing of runoff through the basin.

Road position may also interact with other hydrologic mechanisms proposed to have an effect on peak flow generation. Positioning the road below harvested patches may enhance the opportunity for capture of subsurface water as available soil moisture is increased after harvesting, due either to decreased evapotranspiration or increased snow accumulation and melt in clearcut patches. These interactions between the effects of harvesting and the routing efficiency of roads, which alone may be insignificant, may represent a truly cumulative effect of multiple forest landuse activities.

Table 12. Magnitude of the expected relationship between road hillslope position and mechanisms for road effects on flow routing.

Mechanism	Road position: Channel bottom (riparian zone)	Midslope	Ridgetop
(1) intercepting subsurface flow along road cutbanks and routing it along ditches and through culverts to pre-existing or new channel	Small. Sufficient upslope area to accumulate subsurface flow but effect would be redundant as roads very near existing channel.	Large. Sufficient upslope area to accumulate subsurface flow which if intercepted, is routed to ditch and channel much higher on hillslope than without road.	Small. Insufficient upslope area to accumulate much subsurface flow.
(2) intercepting incoming precipitation and routing it along ditches and through culverts to pre-existing or new channel	Small. Minimal impact of speeded delivery of intercepted flow to channel due to proximity of road to channel.	Moderate. Delivery of intercepted flow to channel system occurs at faster rates than flow infiltrating undisturbed soils.	Moderate.
(3) incising new channels below some culvert outlets	Small. Many culverts empty directly into channel or onto bank.	Moderate. Ditches and culverts empty into preexisting first-order or ephemeral channels which already extend up to midslopes.	Large. Concentration of flow by culverts may initiate channels where flowpaths without roads would not.

Hillslope position was included in the design of this study in order to sample a representative portion of the road network, however no attempt was made to estimate the volume or timing of water intercepted by roads. Future attempts at spatially-explicit modeling of road effects on hydrology should incorporate the varying role of roads in different hillslope positions.

3. Road Age

Roads examined in this study ranged in age from less than 10 to more than 40 years old. Several observations indicate that road age may influence the routing efficiency of a given road segment. Gully formation and the evolution of new channels below culvert outlets would be expected to develop over a number of years, thereby enhancing the effect of roads on flow routing as additional road segments become integrated into the channel network. Many ditches surveyed in this study were highly vegetated. Growth of vegetation in the ditch over time will increase roughness and decrease the hydraulic efficiency of these channels. Therefore, the magnitude of road integration effects would be expected to change over time, increasing due to the formation of gullies but decreasing with vegetation regrowth in ditches.

4. Seasonal Soil Saturation

The variable source area concept provides additional context for assessing the integration of roads and streams. Channel networks are dynamic in nature, expanding and contracting in response to the variable source area contributing to streamflow (Hewlett & Hibbert, 1967). The spatial extent of soil saturation in the watershed controls this dynamic adjustment. Expansion of the channel network may influence the integration of roads in several respects. First, expansion of the channel network may integrate road segments draining to intermittent or ephemeral streams. In addition, gullies that discharge water onto seasonally saturated hillslopes may be integrated only when channel networks are sufficiently extended. Finally, the length of roads functioning as channels, relative to the natural stream network length, would be expected to change throughout a runoff season. These factors may provide an explanation for why roads appear to have a hydrologic effect only in certain seasons and for certain storm magnitudes.

In this study, the length of road connected to channels was measured. In addition, attempts were made to estimate channel length for winter baseflow and average stormflow conditions, in order to assess the change in drainage density by roads and the extent to which that might vary by season of the year. This study was limited, however, in that gully connectivity to streams throughout the year was not measured, and road length contributing to ephemeral streams that channel water only under high-flow conditions was not estimated.

5. Geologic Substrate

Soils and geologic substrate exercise an important role in the extent to which forest roads may impact basin hydrology. Roads constructed on a shallow soil mantle overlying impervious bedrock would be expected to be particularly effective in intercepting subsurface flow and speeding the delivery of runoff in the basin. Roads constructed on highly porous volcanic rocks, such as those found in the Oregon Cascades, would be expected to be less effective in subsurface flow interception.

Soil characteristics and associated erosion rates would also be expected to influence the magnitude of drainage network extension by roads, through the mechanism of gully formation. In Redwood Creek, California, for example, where extensive gullying has occurred by road diversions of streamflow, gully erosion has been mapped and the associated expansion of drainage density was found to range between 6 and 136% for basins within the drainage (Hagans et al, 1984). Smaller increases in drainage density by road-related gullies would be expected in areas where hillslope erosion is less severe. Road drainage surveys conducted in the Oregon Coast Range by Piehl et al (1988) showed that "fluvial erosion" was evident at 38% of the culverts he surveyed. In a survey of culvert installations in the Pistol River basin of the Siskiyou National Forest, Ricks (1993, unpublished data) found that erosion and the formation of gullies had occurred below 24% of the culverts she surveyed. The extent of gullying in these latter two studies is of a similar magnitude to that detected in the Lookout Creek and Blue River basins.

6. Climate

Climatic conditions that result in high soil moisture levels are likely produce conditions conducive to saturated subsurface flows on steep, forested hillslopes (Megahan, 1987). These conditions may arise in regions where precipitation falls during a concentrated portion of the year, where storm systems release large volumes of water in short time periods, and where accumulated snowpacks rapidly melt to release water to the soil. Under these conditions, the likelihood that roads may intercept subsurface flow and substantially alter the routing of runoff is enhanced.

This study was conducted in a region with a xeric climate regime. Dry summers are followed by a period of soil moisture recharge with the commencement of fall storms (Rothacher, 1965). Peak flow events are frequently generated in late winter during so-called "rain-on-snow" events, in which intense rainfall rapidly melts accumulated snowpacks. The hydrologic impact of roads may be different in other regions where different storm types dominate and where precipitation is either rain dominated or snow dominated (e.g. Burroughs et al, 1971; Megahan, 1972).

D. Implications for Road Engineering and Watershed Restoration

Results of this study suggest that specific parts of road networks may contribute disproportionately to the effects of roads on peak flow increases observed by Jones and Grant (in prep, a and b). It seems likely that road segments draining directly (1) to streams and (2) to culverts leading to streams, and possibly (3) those crossing the downslope side of clearcut areas are most likely to respond rapidly to precipitation and thereby contribute to peak flows (Jones and Grant, in prep, a). Watershed restoration practices which modify road segments in these categories may be most effective at reducing road effects on peak flows. Restoration practices could be designed to disperse water to subsurface pathways by increasing culvert density, outsloping road surfaces, or removing impervious road-bed material and restoring vegetation on hillslopes.

VI. CONCLUSIONS

This observational study suggests that roads function hydrologically to modify streamflow generation in forested watersheds by altering the spatial distribution of surface and subsurface flowpaths. Nearly 60% of the road network in Lookout Creek and Blue River drains to streams and gullies and is therefore hydrologically integrated with the stream network. Field observations suggest that roadside ditches and gullies function as effective surface flowpaths which substantially increase drainage density during storm events. Thus roads may alter basin hydrographs by extending the surface flow network. Since the volume of runoff from roads and its speed of delivery to the basin outlet (which were not measured in this study) vary according to road design, road hillslope position, road age, seasonal soil saturation, geologic substrate, and climate, these factors may explain the conflicting results from paired-watershed studies of road effects. Results of this study suggest that addressing and mitigating the integration of roads with streams may be an obvious and effective first step toward watershed restoration. Further research is needed to fully understand the downstream hydrologic effects of these integrated road segments on the generation of peak flows.

VII. LITERATURE CITED

Anderson, H. W. and R. L. Hobba. 1959. Forests and floods in the northwestern United States. Publication 48, International Association of Scientific Hydrology, pp. 30-39.

Anderson, P. T., M. R. Pyles, and J. Sessions. 1987. The operation of logging trucks on steep, low-volume roads. 4th International Conference on Low-Volume Roads. Volume 1-2. Transportation Research Board, National Research Council, Washington, D.C. Transportation Research Record 1106, pp 104-111.

Berntsen, C. M. and J. Rothacher. 1959. A guide to the H.J. Andrews Experimental Forest. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. 21pp.

Bilby, R. E., K. Sullivan, S. H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Science, 35(2): 453-468.

Boots, B. N. and A. Getis. 1988. Point Pattern Analysis. Sage Publications, London.

Burroughs, E. R., Jr., M. A. Marsden and H. F. Haupt. 1971. Volume of snowmelt intercepted by logging roads. ASCE National Water Resources Engineering Meeting, Phoenix, Arizona, Jan. 11-15, 1971. 24pp.

Burroughs, E. R., Jr. F. J. Watts, and D. F. Haber. 1984. Surfacing to reduce erosion of forest roads built in granitic soils. Symposium on effects of land use on erosion and slope stability, Hawaii. pp. 255-264.

Carow, J. and R. R. Silen. 1957. Using the staggered setting system, what are the logging costs? The Timberman, 58(4): 48-53.

Cederholm, C. J. and E. O. Salo. 1979. The effects of logging road landslide siltation on the salmon and trout spawning gravels of Stequaleho Creek and the Clearwater River basin, Jefferson County, Washington, 1972-1978. Publication FRI-UW-7915, University of Washington Fisheries Research Institute, Seattle. 99pp.

Christner, J. and R. D. Harr. 1982. Peak streamflows from the transient snow zone, Western Cascades, Oregon. Proceedings of the 50th Western Snow Conference, Colorado State University, Fort Collins. pp. 27-38.

Connelly, B. A., D. P. Lettenmaier, and T. W. Cundy. Manuscript in preparation. Effects of forest practices on extreme floods in western Washington.

Duncan, S. H. 1986. Peak stream discharge during thirty years of sustained yield timber management in two fifth order watersheds in Washington State. Northwest Science, 60(4): 258-264.

Duncan, S. H., R. E. Bilby, and J. T. Heffner. 1987. Transport of road-surface sediment through ephemeral stream channels. Water Resources Bulletin, 23(1): 113-119.

Dunne, T. and L. B. Leopold. 1978. Water in Environmental Planning. W. H. Freeman and Co., San Francisco. 818pp.

Dyrness, C. T. 1967. Mass soil movements in the H. J. Andrews Experimental Forest. USDA Forest Service, Research Paper PNW-42, Pacific Northwest Forest and Range Experiment Station, Portland, OR, 12pp.

Dyrness, C. T. 1969. Hydrologic properties of soil on three small watersheds in the western Cascades of Oregon. USDA Forest Service, Research Note PNW-111, Pacific Northwest Forest and Range Experiment Station, Portland, OR, 17pp.

Eberhardt, L. L. and J. M. Thomas. 1991. Designing environmental field studies. Ecological Monographs, 61(1):53-73.

Foltz, R. B. and E. R. Burroughs. 1990. Sediment production from forest roads with wheel ruts. Watershed Planning and Analysis in Action. Symposium Proceedings of IR Conference, ASCE, Colorado. pp. 266- 275.

Forest Ecosystem Management Assessment Team. 1993. Forest ecosystem management: An ecological, economic, and social assessment. U.S. Government Printing Office: 1993-793-071.

Franklin, J. F. and C. T. Dyrness. 1969. Vegetation of Oregon and Washington. USDA Forest Service Research, Paper PNW-80, Pacific Northwester Forest and Range Experiment Station, Portland, OR, 216pp.

Greenland, D. 1993. The climate of the H.J. Andrews Experimental Forest and its regional synthesis. Final report for the USDA Forest Service, Pacific Northwest Research Station, Cooperative Agreement No. PNW 92-0221. 39pp.

Hagans, D. K., W. E. Weaver, and M. A. Madej. 1984. Long term on-site and off-site effects of logging and erosion in the Redwood Creek basin, Northern California. NCASI Technical Bulletin No. 490, pp 38-66. New York.

Harr, R. D. 1976. Forest practices and streamflow in western Oregon. USDA Forest Service, General Technical Report PNW-49, Pacific Northwest Forest and Range Experiment Station, Portland, OR, 18pp.

Harr, R. D. 1977. Water flux in soil and subsoil on a steep forested slope. Journal of Hydrology, 33: 37-58.

Harr, R. D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. Journal of Hydrology, 53:277-304.

Harr, R. D. 1986. Effects of clearcutting on rain-on-snow runoff in western Oregon: a new look at old studies. Water Resources Research, 22(7): 1095-1100.

Harr, R. D., R. L. Fredricksen, and J. Rothacher. 1979. Changes in streamflow following timber harvest in southwestern Oregon. USDA Forest Service, Research Paper, PNW-249, Pacific Northwest Forest and Range Experiment Station, Portland, OR, 22 pp.

Harr, R. D., W. C. Harper, J. T. Krygier, and F. S. Hsieh. 1975. Changes in storm hydrographs after road building and clear cutting in the Oregon Coast Range. Water Resources Research, 11(3): 436-444.

Hewlett, J. D. and A. R. Hibbert. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. *In* W. E. Sopper and H. W. Lull (eds.), International Symposium on Forest Hydrology, pp. 275-290. Pergamon Press, New York.

Hibbert, A. R. 1967. Forest treatment effects on water yield. *In* W. E. Sopper and H. W. Lull (eds.), International Symposium on Forest Hydrology, p. 527-543. Pergamon Press, New York.

Holland, P. W. 1986. Statistics and causal inference. Journal of the American Statistical Association, 81(396): 945-960.

Jensen, F. and F. Cole. 1965. South Fork Salmon River storm and flood report. U.S. Department of Agriculture, Forest Service, Payette National Forest, McCall, ID. 15pp.

Jenson, S. K. and J. O. Domingue. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing, 54(11): 1593-1600.

Jones, J. A. and G. E. Grant. Manuscript in preparation, a. Cumulative effects of forest harvest on peak streamflow in the western Cascades of Oregon. I: small basins.

Jones, J. A. and G. E. Grant. Manuscript in preparation, b. Cumulative effects of forest harvest on peak streamflow in the western Cascades of Oregon. II: large basins.

King, J. G. and L. C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in North Central Idaho. Water Resources Research, 20(8): 1159-1163.

Kiser, J. D. 1992. Photogrammetric uses of a new-generation analytical stereoplotter in forestry. M.S. Thesis, Oregon State University, Corvallis, OR. 156pp.

Kramer, B. 1993. A road design process for low volume recreation and resource development. M.S. Thesis, Oregon State University, Corvallis, OR. 104pp.

Leopold, L. B., M. G. Wolman and J. P. Miller. 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Co., San Francisco. 522pp.

Lienkaemper, G. W. 1977. The annual expansion and contraction of a stream network. (Abs) A.A.A.S. San Francisco, Ca.

Luce, C. H. and T. W. Cundy. 1994. Parameter identification for a runoff model for forest roads. Manuscript in press, Water Resources Research.

Lyons, J. K. and R. L. Beschta. 1983. Land use, floods, and channel changes: Upper Middle Fork Willamette River, Oregon (1936-1980). Water Resources Research, 19(2): 463-471.

Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. National Symposium on Watersheds in Transition, American Water Resources Association and Colorado State University. pp 350-356.

Megahan, W. F. 1987. Effects of forest roads on watershed function in moutainous areas, pp 335-347. *In* Balasubramaniam et al (eds.), Environmental Geotechnics and Problematic Soils and Rocks. Balkema, Rotterdam.

Megahan, W. F., N. F. Day and T. M. Bliss. 1978. Landslide occurrence in the western and central northern Rock Mountain physiographic province in Idaho. *In* C. T. Youngberg (ed), Proceedings of the 5th No. American forest soils conference, Fort Collins, Co. Colorado State University; August 1978. pp. 116-139.

Megahan, W. F., and W. J. Kidd. 1972. Effect of logging roads on sediment production rates in the Idaho batholith. Research Paper INT-123. Ogden, Utah: U.S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 14 pp.

Montgomery, D. Manuscript in preparation. Road surface drainage, channel initiation, and slope instability.

Nulsen, R. A. 1985. Hillside seeps. Journal of Agriculture, Western Australia, 26(4):128-129.

Oregon Department of Forestry. 1991. Forest Practices Rules. Salem, OR. 146pp.

Piehl, B. 1987. An evaluation of culverts on low volume forest roads in the Oregon Coast Range. M.S. Thesis, Oregon State University, Corvallis, OR. 78 pp.

Piehl, B. T., R. L. Beschta, and M. R. Pyles. 1988. Ditch-relief culverts and low-volume forest roads in the Oregon Coast Range. Northwest Science, 62(3): 91-98.

Pyles, M. R., A. E. Skaugset, and T. Warhol. 1989. Culvert design and performance on forest roads. Presented at the 12th Annual Council on Forest Engineering Meeting, Coeur d'Alene, ID. August 27-30, 1989.

Reid, L. M. 1981. Sediment production from gravel-surfaced forest roads, Clearwater basin, Washington. Publication FRI-UW-8108, University of Washington Fisheries Research Institute, Seattle. 247pp.

Reid, L. M. and T. Dunne. 1984. Sediment production from road surfaces. Water Resources Research, 20: 1753-1761.

Rothacher, J. 1965. Streamflow from small watersheds on the western slope of the Cascade range of Oregon. Water Resources Research, 1(1): 125-134.

Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. Water Resources Research, 6(2): 653-658.

Rothacher, J. 1971. Regimes of streamflow and their modification by logging. Proceedings of a Symposium , Forest Land Uses and Stream Environment. Oregon State University Cooperative Extension Program - School of Forestry and Dept. of Fisheries and Wildlife. pp 40-54.

Rothacher, J. 1973. Does harvest in west slope Douglas-fir increase peak flow in small forest streams? USDA Forest Service Research Paper, PNW-163. 13pp.

Ruth, R. H. and R. R. Silen. 1950. Suggestions for getting more forestry in the logging plan. USDA Forest Service, Research Note 72, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 19pp.

Sedlak, O. 1985. General principles of planning forest road nets. In Logging Transport in Steep Terrain, Report of the fourth FAO/Austria Training Course on Mountain Forest Roads and Harvesting, Ossiach and Ort, Austria, 1983.

Sessions, J. 1986. Can income tax rules affect management strategies for forest roads? Western Journal of Applied Forestry, 1(1):26-28.

Sessions, J., J. C. Balcom, and K. Boston. 1987. Road location and construction practices: effects on landslide frequency and size in the Oregon Coast Range. Western Journal of Applied Forestry, 2(4): 119-124.

Silen, R. R. 1955. More efficient road patterns for a Douglas fir drainage. The Timberman, 56(6): 82, 85-86, 88.

Silen, R. R. and H. J. Gratkowski. 1953. An estimate of the amount of road in the staggered-setting system of clear cutting. USDA Forest Service, Research Note 92, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 4pp.

Sullivan, K. O. and S. H. Duncan. 1981. Sediment yield from road surfaces in response to truck traffic and rainfall. Weyerhaeuser Research Report, Western Forestry Research Center, Centralia, WA. 46pp.

Swanson, F. J., L. E. Benda, S. H. Duncan, G. E. Grant, W. F. Megahan, L. M. Reid, and R. R. Ziemer. 1987. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. In: E. O. Salo and T. W. Cundy, eds. Streamside Management: Forestry and Fishery Interactions, Proceedings of a symposium, 1986. Contribution 57. Seattle: University of Washington, Institute of Forest Resources. pp. 9-38.

Swanson, F. J. and C. T. Dyrness. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3: 392-396.

Swanson, F. J. and M. E. James. 1975. Geology and geomorphology of the H. J. Andrews Experimental Forest, Western Cascades, Oregon. USDA Forest Service, Research Paper PNW-188, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 14pp.

Tabachnick, B. G. and L. S. Fidell. 1989. Using multivariate statistics, second edition. Harper & Row, New York. 746 pp.

Turner, M. G. 1989. Landscape ecology: the effects of pattern on process. Annual Reviews of Ecology and Systematics, 20:171-197.

U.S.D.A. Forest Service. 1986. Road Drainage Structures Handbook, FSH 7709.56B.

U.S.D.A. Forest Service. 1987. Road Preconstruction Handbook, FSH 7709.56, Amendment 1.

Wiens, J. A. 1989. Spatial scaling in ecology. Functional Ecology, 3: 385-397.

Wright, K. A., K. H. Sendek, R. M. Rice, and R. B. Thomas. 1990. Logging effects on streamflow: storm runoff at Casper Creek in Northwestern California. Water Resources Research, 26(7): 1657-1667.

Ziemer, R. R. 1981. Storm flow response to road building and partial cutting in small streams of northern California. Water Resources Research, 17(4): 907-917.

Appendices

Appendix 1:

Sample field data form

Field data form was used to record (a) continuous length along transect at which each culvert was located; (b) road grade for the portion of road routed to each culvert; (c) classification of culvert outlet routing to (i) stream channel, (ii) gully, or (iii) subsurface flow; (d) description of site; (e) culvert size, and (f) comments on condition of ditch and cutbank. Summary columns were used to tally road length to each outlet category for final calculations.

			(a)	(b)	(c)	(d)	(e)	(f)	
summary							culvert	Com ments	
ch	gully	ssf	length	grade	rtng	description	size (in)	ditch	banks

Appendix 2:

Summary of field survey results

Table A-1: Summary of field survey results

Transect #	1		2		3		4		5		6		7		8		9	
No. culverts to:																		
1) ssf	12	67	9	36	8	38	3	25	7	64	3	27	5	50	6	33	2	13
2) gully	1	6	9	36	2	10	1	8	1	9	3	27	3	30	5	28	3	20
3) natural channel	5	28	7	28	11	52	8	67	3	27	5	45	2	20	7	39	10	67
2&3)	6	33	16	64	13	62	9	75	4	36	8	73	5	50	12	67	13	87
total	18		25		21		12		11		11		10		18		15	
Total length of ditch to: (km)																		
1) ssf	1.40	70.0	0.60	32.1	0.75	39.9	0.40	21.1	1.20	62.8	0.52	26.8	1.03	55.4	0.75	38.5	0.08	4.4
2) eph/gully	0.12	6.0	0.82	43.9	0.22	11.7	0.15	7.9	0.33	17.3	0.40	20.6	0.70	37.6	0.65	33.3	0.35	19.1
3) natural channel	0.48	24.0	0.45	24.1	0.91	48.4	1.35	71.1	0.38	19.9	1.02	52.6	0.13	7.0	0.55	28.2	1.40	76.5
2 & 3)	0.60	30.0	1.27	67.9	1.13	60.1	1.50	78.9	0.71	37.2	1.42	73.2	0.83	44.6	1.20	61.5	1.75	95.6
total	2.00		1.87		1.88		1.90		1.91		1.94		1.86		1.95		1.83	

Results after Resurvey

*R = resurveyed

Transect #	1		2		3		4		5		* R 6		7		8		9	
No. of culverts to																		
1) ssf											3	27						
2) eph/gully											2	18						
3) natural channel											6	55						
2 & 3)											8	73						
total											11							
Total length of ditch to: (km)																		
1) ssf											0.45	23.2						
2) eph/gully											0.27	13.9						
3) natural channel											1.22	62.9						
2 & 3)											1.49	76.8						
total											1.94							
% change (after resurvey)																		
1) ssf											-3.6							
2) eph/gully											-6.7							
3) natural channel											10.3							
2 & 3)																		

Table A-1 (continued): Summary of field survey results

10		11		12		13		14		15		16		17		18		19	
9	47	3	20	3	21	5	45	6	50	3	25	7	39	7	58	2	22	5	42
3	16	4	27	2	14	1	9	2	17	5	42	7	39	3	25	1	11	5	42
7	37	8	53	9	64	5	45	4	33	4	33	4	22	2	17	6	67	2	17
10	53	12	80	11	79	6	55	6	50	9	75	11	61	5	42	7	78	7	58
19		15		14		11		12		12		18		12		9		12	
1.05	55.3	0.78	40.4	0.80	43.5	0.75	38.9	1.00	50.0	0.33	16.5	0.78	43.1	0.76	57.1	0.33	18.9	0.98	56.0
0.33	17.4	0.42	21.8	0.17	9.2	0.25	13.0	0.38	19.0	0.92	46.0	0.65	35.9	0.27	20.3	0.20	11.4	0.50	28.6
0.52	27.4	0.73	37.8	0.87	47.3	0.93	48.2	0.62	31.0	0.75	37.5	0.38	21.0	0.30	22.6	1.22	69.7	0.27	15.4
0.85	44.7	1.15	59.6	1.04	56.5	1.18	61.1	1.00	50.0	1.67	83.5	1.03	56.9	0.57	42.9	1.42	81.1	0.77	44.0
1.90		1.93		1.84		1.93		2.00		2.00		1.81		1.33		1.75		1.75	

10		* R 11		12		13		14		15		16		* R 17		* R 18		19	
		4	27											7	58	4	44		
		3	20											3	25	1	11		
		8	53											3	25	9	100		
		11	73											6	50	10	111		
		15												13		14			
		0.68	35.2											0.68	51.1	0.53	30.3		
		0.33	17.1											0.37	27.8	0.22	12.6		
		0.98	50.8											0.28	21.1	1.20	68.6		
		1.31	67.9											0.65	48.9	1.42	81.1		
		1.99												1.33		1.95			
		-5.2												-6.0		11.4			
		-4.7												7.5		1.1			
		13.0												-1.5		-1.1			

Table A-1 (continued): Summary of field survey results

20		21		22		23		24		25		26		27		28		29		30		31	
5	36	4	31	2	33	3	30	2	14	9	56	8	53	9	100	10	77	7	41	11	61	7	44
4	29	6	46	2	33	1	10	5	36	3	19	3	20	0	0	2	15	4	24	5	28	5	31
5	36	3	23	2	33	6	60	7	50	4	25	4	27	0	0	1	8	6	35	2	11	4	25
9	64	9	69	4	67	7	70	12	86	7	44	7	47	0	0	3	23	10	59	7	39	9	56
14		13		6		10		14		16		15		9		13		17		18		16	
0.73	36.3	0.53	30.6	0.37	19.8	0.53	25.7	0.43	21.5	1.17	58.2	0.98	50.5	1.83	100.0	1.20	71.9	0.73	36.9	1.13	58.5	0.80	44.0
0.48	23.9	0.70	40.5	1.08	57.8	0.25	12.1	0.82	41.0	0.42	20.9	0.33	17.0	0.00	0.0	0.30	18.0	0.40	20.2	0.50	25.9	0.57	31.3
0.80	39.8	0.50	28.9	0.42	22.5	1.28	62.1	0.75	37.5	0.42	20.9	0.63	32.5	0.00	0.0	0.17	10.2	0.85	42.9	0.30	15.5	0.45	24.7
1.28	63.7	1.20	69.4	1.50	80.2	1.53	74.3	1.57	78.5	0.84	41.8	0.96	49.5	0.00	0.0	0.47	28.1	1.25	63.1	0.80	41.5	1.02	56.0
2.01		1.73		1.87		2.06		2.00		2.01		1.94		1.83		1.67		1.98		1.93		1.82	

20		21		22		23		* R 24		25		* R 26		27		28		* R 29		* R 30		* 31	
								3	21			6	40					6	35	10	56		
								7	50			4	27					5	29	5	28		
								6	43			6	40					6	35	3	17		
								13	93			10	67					11	65	8	44		
								16				16						17		18			
								0.48	24.0			0.67	34.5					0.55	27.8	1.07	55.4		
								0.88	44.0			0.50	25.8					0.58	29.3	0.57	29.5		
								0.63	31.5			0.73	37.6					0.85	42.9	0.30	15.5		
								1.51	75.5			1.23	63.4					1.43	72.2	0.87	45.1		
								1.99				1.90						1.98		1.94			
								2.5				-16.0						-9.1		-3.1			
								3.0				8.8						9.1		3.6			
								-6.0				5.2						0.0		0.0			

Table A-1 (continued): Summary of field survey results

	Mean	Std Dev	Total	%
No. culverts to:				
1) ssf			182	42
2) gully			101	23
3) natural channel			153	35
2&3)			254	58
total			436	
Total length of ditch to: (km)				
1) ssf	42.7	19.7	24.72	
2) eph/gully	23.5	13.3	13.68	
3) natural channel	33.8	18.9	19.83	
2 & 3)	57.3	19.7	33.51	
total			58.23	

Appendix 3:

Statistical analysis of gullying below ditch-relief culverts

```
[o] GLIM 3.77 update 1 (copyright)1985
   Royal Statistical Society, London
[o]
[i] ? $units 275 $data spac gull grad exce slop $dinput 22 $
[i] File name? culvert2
[i] ? $calc n=spac/spac $look n $
[i] ? $yvar gull $error b n $link g $
[i] ? $fit $
[o] scaled deviance = 363.73 at cycle  4
[o]            d.f. = 274
[o]
[o]
[i] ? $fit +spac+grad+spgr $dis e $
[o] scaled deviance = 360.25 (change =    -3.48) at cycle  4
[o]            d.f. = 271    (change =    -3    )
[o]
[o]          estimate         s.e.      parameter
[o]     1     -0.5305       0.5626      1
[o]     2      -4.475        5.832      SPAC
[o]     3   -0.004637      0.07096      GRAD
[o]     4      0.7367       0.7476      SPGR
[o]     scale parameter taken as  1.000
[o]
[i] ? $fit +slop $dis e $
[o] scaled deviance = 339.90 (change =   -20.35) at cycle  4
[o]            d.f. = 270    (change =    -1    )
[o]
[o]          estimate         s.e.      parameter
[o]     1     -0.8262       0.5863      1
[o]     2      -5.621        6.040      SPAC
[o]     3    -0.03042      0.07357      GRAD
[o]     4      0.8594       0.7684      SPGR
[o]     5       1.168       0.2625      SLOP
[o]     scale parameter taken as  1.000
[o]
[i] ? $calc spsl=spac*slop $calc grsl=grad*slop
   $fit +spsl+grsl $dis e $
[o] scaled deviance = 331.22 (change =    -8.68) at cycle  4
[o]            d.f. = 268    (change =    -2    )
[o]
[o]          estimate         s.e.      parameter
[o]     1     -0.2156       0.6761      1
[o]     2      -15.95        7.795      SPAC
[o]     3    -0.02189      0.08054      GRAD
[o]     4       1.117       0.8668      SPGR
[o]     5      0.2482       0.7893      SLOP
[o]     6       16.03        6.008      SPSL
[o]     7    -0.05113      0.07876      GRSL
[o]     scale parameter taken as  1.000
[o]
```

```
[i] ? $fit -grsl $dis e $
[o] scaled deviance = 331.64 (change =   +0.42) at cycle  4
[o]            d.f. = 269    (change =   +1    )
[o]
[o]         estimate        s.e.     parameter
[o]    1     -0.1022      0.6456     1
[o]    2      -15.57       7.631     SPAC
[o]    3    -0.03961     0.07583     GRAD
[o]    4       1.083      0.8627     SPGR
[o]    5     -0.1293      0.5348     SLOP
[o]    6       16.14       6.002     SPSL
[o]    scale parameter taken as  1.000
[o]
[i] ? $fit -grad-spgr $dis e $
[o] scaled deviance = 334.44 (change =   +2.80) at cycle  4
[o]            d.f. = 271    (change =   +2    )
[o]
[o]         estimate        s.e.     parameter
[o]    1     -0.3711      0.3732     1
[o]    2      -8.222       4.391     SPAC
[o]    3    -0.08103      0.5322     SLOP
[o]    4       15.65       5.959     SPSL
[o]    scale parameter taken as  1.000

[i] ? $stop $
```

Appendix 4:

Selected measurements of ditchflow

Table 4-2: Selected Measurements of Ditchflow

Location: Date:	Lookout Creek, Road 1506 at WS1 3/19/93	Blue River, Road 1509 6/8/93
Ditch cross-sectional area:	9 in^2	31 in^2
Velocity *:	10 in/sec x 0.8 = 8 in/sec	18 in/sec x 0.8 = 14.4 in/sec
Discharge:	8 in/sec x 9 in^2 = 72 in^3/sec 72 in^3/sec x 16.39 ml/in^3 = 1180.1 ml/sec	14.4 in/sec x 31 in^2 = 446.4 in^3/sec 446.4 in^3/sec x 16.39 ml/in^3 = 7316.5 ml/sec

* Average value of multiple trials measured with a floating cork and multiplied by 0.8 (after Leopold, Wolman and Miller, 1964, p. 167).