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# CHANNEL NETWORK EXTENSION BY LOGGING ROADS IN TWO BASINS, WESTERN CASCADES, OREGON[1]

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ABSTRACT: Based on field surveys and analysis of road networks using a geographic information system (GIS), we assessed the hydrologic integration of an extensive logging-road network with the stream network in two adjacent 62 and 119 $km^2$ basins in the western Cascades of Oregon. Detailed surveys of road drainage for 20 percent of the 350 km road network revealed two hydrologic flow paths that link roads to stream channels: roadside ditches draining to streams (35 percent of the 436 culverts examined), and roadside ditches draining to culverts with gullies incised below their outlets (23 percent of culverts). Gully incision is significantly more likely below culverts on steep (> 40 percent) slopes with longer than average contributing ditch length. Fifty-seven percent of the surveyed road length is connected to the stream network by these surface flowpaths, increasing drainage density by 21 to 50 percent, depending on which road segments are assumed to be connected *to* streams. We propose a conceptual model to describe the hydrologic function of roads based on two effects: (1) a volumetric effect, increasing the volume of water available for quickflow and (2) a timing effect, altering flow-routing efficiency through extensions to the drainage network. This study examines the second of these two effects. Future work must quantify discharge along road segments connected to the stream network in order to more fully explain road impacts on basin hydrology.

(KEY TERMS: forest hydrology; drainage networks; logging roads; culverts; gullies.)

## INTRODUCTION

Environmental impacts of logging roads have received considerable attention in both research and management circles in recent decades. Road construction has been associated with a number of effects on hydrologic and geomorphic processes, including increased rates of surface erosion (Reid and Dunne, 1984; Duncan et al., 1987) and landsliding (Swanson and Dyrness, 1975; Megahan et al., 1978), changes in peak flow magnitude (Harr et al., 1975; King and Tennyson, 1984), and attendant impacts on stream sedimentation and channel morphology (Cederholm and Salo, 1979; Beschta, 1978; Bilby et al., 1989).

In a recent investigation of long-term hydrologic records from small (1 $km^2$) and large (50-500 $km^2$) basins in western Oregon, Jones and Grant (1996) found significant changes in peak flow magnitude and timing associated with historical trends in logging and road construction. In the small, experimental basins they examined, peak flows increased by 50 percent in Watershed 3 in the five-year period following road construction and logging in the basin. This increase, attributed to the combined treatments of road construction and the harvesting of 25 percent of the basin area, was equivalent to that which was observed on Watershed 1, which was 100 percent clearcut without roads. A trend of increased magnitude in peak flows was also noted in the large-basin pairs examined, particularly in Lookout Creek and Blue River which had approximately the same landuse as Watershed 3 - 25 percent of the basin area harvested and 2-3 km $km^{-2}$ in roads.

The role of logging roads in altering the magnitude and timing of peak flows remains poorly understood. Taken collectively, the results of paired-watershed studies examining the effects of roads on basin hydrology are inconclusive. Roads alone produced statistically significant changes in peak flows in some small paired basins in a study in Idaho (King and Tennyson, 1984), but not in an Oregon study (Jones and Grant, 1996). Clearcut logging with roads was associated with a significant increase in peak flows in small (< 5 $km^2$) paired-basin experiments in Oregon

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(Ham et al., 1975; Harr et al., 1979; Jones and Grant, 1996), but not in an experiment in California (Ziemer, 1981; Wright et al., 1990). Studies of large (> 50 km2) forested basins subjected to dispersed harvesting and road construction over several decades found increased peak flows associated with the proportion of basin area in roads and clearcuts in some cases (Anderson and Hobba, 1959; Christner and Harr, 1982; Jones and Grant, 1996), but not in others (Duncan, 1986).

Previous watershed studies have not examined the mechanisms by which roads influence changes in peak flow hydrology. This study was initiated to explore mechanisms by which roads may alter routing efficiency in a basin. Specifically, we examined the type and extent of hydrologic flow paths linking road segments to stream channels in two adjacent basins in the western Cascades of Oregon.

## CONCEPTUAL MODEL

We propose a conceptual model to describe the hydrologic function of roads based on two effects: (1) a volumetric effect, increasing the volume of water available for quickflow; and (2) a timing effect, altering flow routing efficiency through extensions to the drainage network (Figure 1).

The volumetric effect of roads operates at the hillslope scale (Figure 1). Precipitation on hillslopes is partitioned to slow subsurface drainage contributing to baseflow (Qbase) and rapid surface and subsurface runoff contributing to quickflow (Qquick). The hydrograph represents the summation over time of the volumes contributed by these two components, expressed as

$$Q(t) = Q_{base} + Q_{quick} \tag{1}$$

Roads increase the total volume of water available for quickflow in two ways. Overland flow is generated by the interception of precipitation on compacted road surfaces with low infiltration capacities (Reid and Dunne, 1984; Luce and Cundy, 1994). In addition, shallow subsurface flow may be intercepted at road cutbanks and converted to rapid surface runoff (Megahan, 1972; Sullivan and Duncan, 1981). This effect of increasing total quickflow volume may be expressed as

$$\Delta Q_{quick} = Q_{intercepted} + Q_{subsurface \rightarrow surface} \tag{2}$$

The timing effect of roads operates at the basin scale (Figure 1). The length and arrangement of stream channels determines the flow-routing efficiency of the basin (Leopold et al., 1964). Drainage density, often used as an index of drainage efficiency,

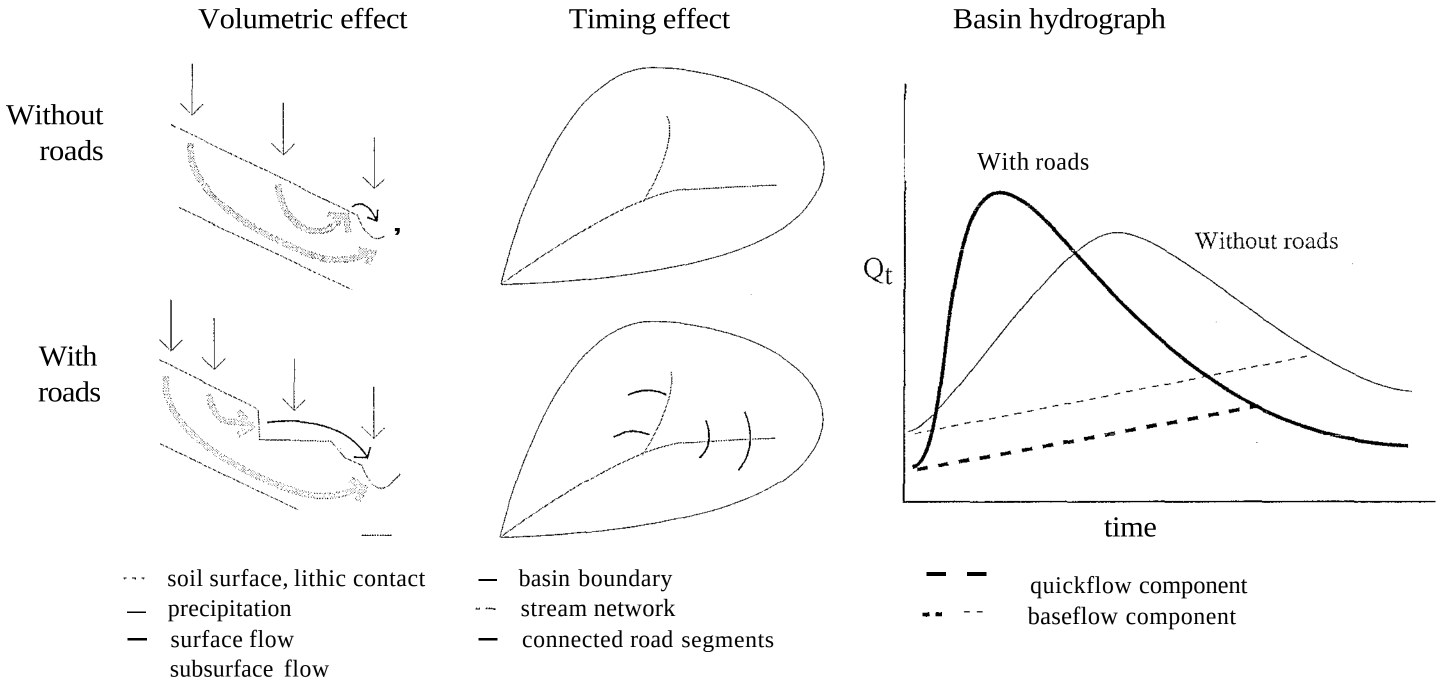

Figure 1. A Conceptual Model of the Hydrologic Function of Roads Based on Two Effects: (1) a volumetric effect, increasing the total volume of water available for quickflow; and (2) a timing effect, altering the flow routing efficiency through extensions to the drainage network (*see* text).

is defined as the sum of stream length (LS) over the basin area

$$D_d = \frac{\sum L_S}{A} \qquad (3)$$

We propose that roads modify drainage density by extending the total length of effective surface flowpaths in a basin, expressed as

$$D'_d = \frac{\sum\left(L_S + L_{Rc} + L_{Rg} + L_G\right)}{A} \qquad (4)$$

where $\sum L_{Rc}$ represents the length of road segments discharging runoff directly to stream channels, $\sum L_{Rg}$ represents the length of road segments discharging runoff to hillslopes where channelized surface flow occurs in newly-eroded gullies, and $\sum L_G$ represents the length of those gullies connecting roads to streams on previously unchanneled hillslopes (Figure 2). We define gullies in this study as surface flowpaths evident at road culverts created either by chronic channel incision on hillslopes or episodic scour by landslides.

In this study, we focused on assessing road effects at the drainage-basin scale. We examined drainage network length in two basins and the extent to which roads modify drainage density by extending the channel network.

## METHODS

### *Approach*

The study included three components: (1) determination of the increase in drainage density attributable to road-stream connectivity in the Lookout Creek and Blue River basins; (2) examination of factors contributing to road-stream connectivity, particularly the formation of gullies; and *(3)* comparison of the timing and spatial distribution of road construction in Lookout vs. Blue River to evaluate whether road-stream

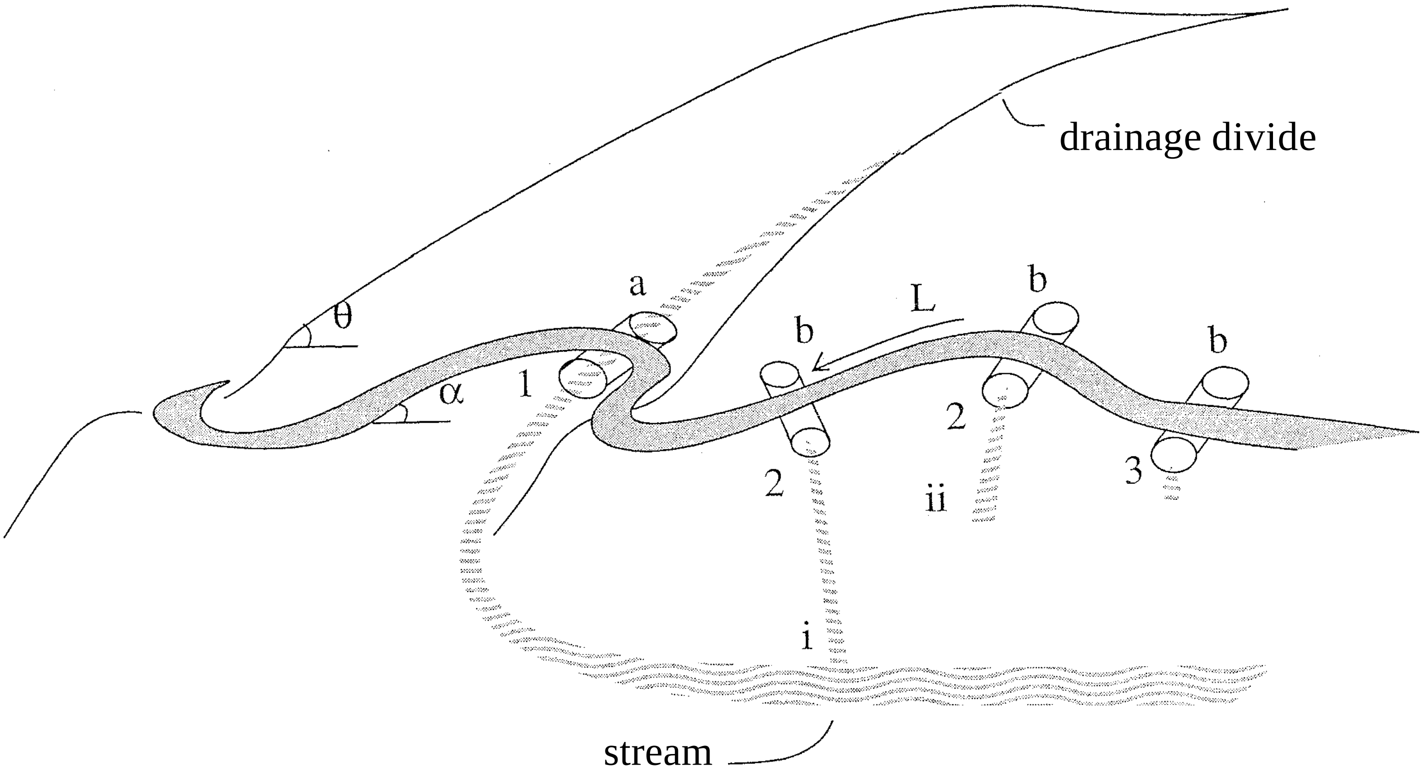

Figure 2. Road Drainage Structures on Forest Roads. Stream-crossing culverts which route a stream below a road (a) and ditch-relief culverts (b) were classified according to whether they discharged directly to a stream channel (1), onto hillslopes below roads where gully incision occurs (2), or where water reinfiltrates into the hillslope soil (3). Gully incision may provide a continuous flowpath to streams (i) or may function as a discontinuous channel segment (ii). The length of the road segment draining to the culvert (L), the road grade $(\alpha)$, and the hillslope angle $(\theta)$ were used to test predictions of the occurrence of gullies.

connectivity provides a plausible explanation for the observed increase in peak flows in these two basins reported by Jones and Grant (1996).

## *Study Area*

The study was conducted in Lookout Creek (62 km$^2$) and Blue River (119 km$^2$), two contiguous fifth-order basins located approximately 70 km east of Eugene in the western Cascades of Oregon (Figure 3, Table 1). Lookout Creek drains the H. J. Andrews Experimental Forest, where both paired-basin experiments and longitudinal studies have assessed the effects of forest harvesting and roads on small-basin hydrology, sediment yield and other processes.

TABLE 1. Physical Characteristics of the Study Basins.

| | **Lockout Creek** | **Blue River** |
|---|---|---|
| Basin Area (km2) | 62 | 119 |
| Elevation Range (m) | 400-1600 | 400-1600 |
| Slope Angles (%) | 0-160 | 0-173 |
| Cumulative Percent of Basin Clearcut | 22 | 25 |
| Road Length (km) | 119 | 230 |
| Road Density (km km$^{-2}$) | 1.9 | 1.9 |
| Area of Basin in Road (%)* | 3.1 | 3.1 |

*Computed using average width of road and cut and fill of 16 m (59.9 ft).

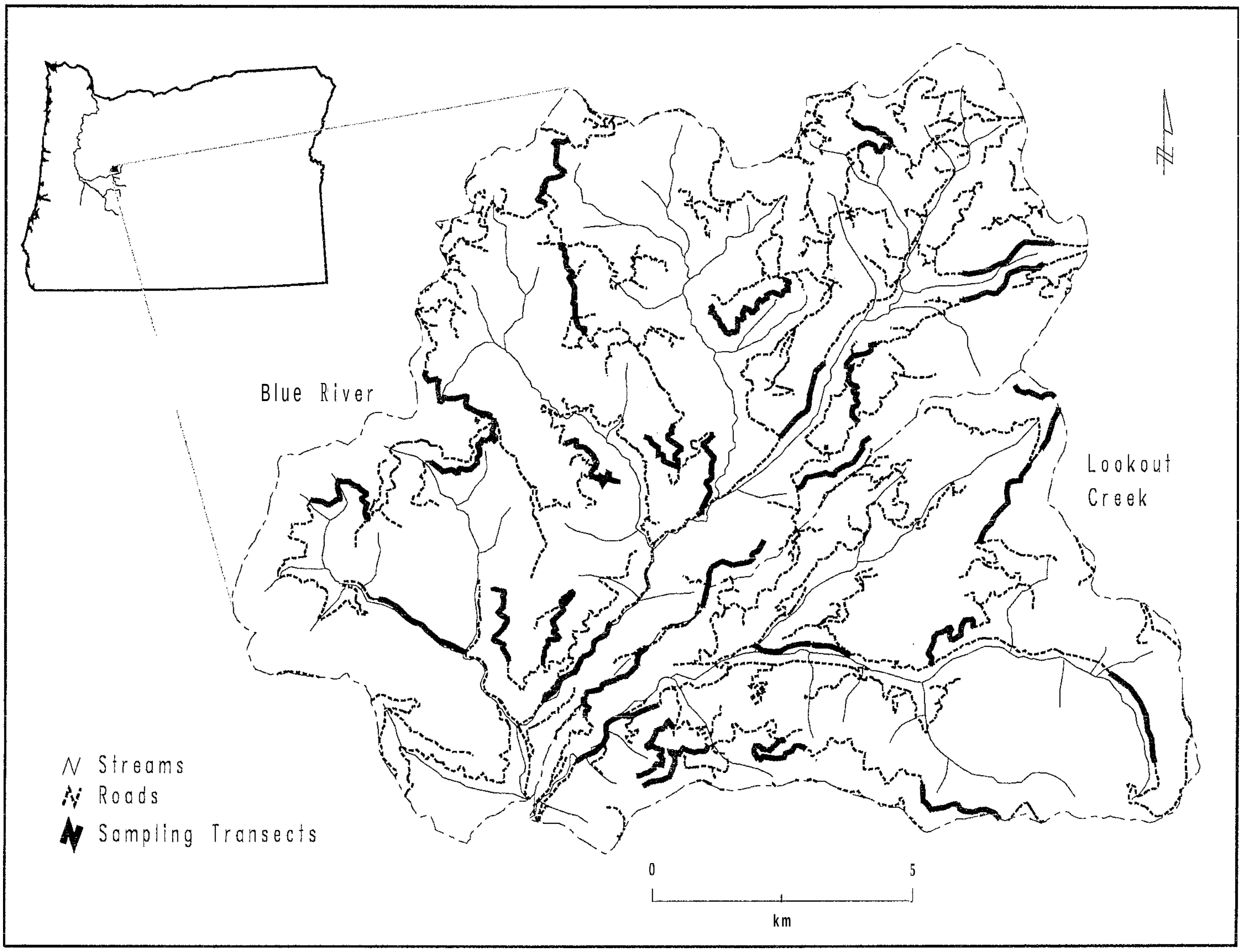

Figure 3. Study Area and Location of Road Transects Sampled in This Study.

Elevations in the two basins range from 400 meters to more than 1500 meters with slopes ranging from 0 to over 80 percent. Average annual precipitation is approximately 225 cm, and typically falls as rain between October and May at the lower elevations and as snow at higher elevations (Greenland, 1994).

The basins are underlain by geomorphically unstable, hydrothermally-altered, volcaniclastic rocks in the lower elevations, and by stable lava flows at higher elevations. The geomorphology of the basins reflects the action of glacial, fluvial and mass wasting processes (Swanson and James, 1975). Colluvial deposits as deep as 15 meters underlie soils in some portions of the basins (Dyrness, 1969). Soils are clay loams, derived from andesites and basalts and silty clays, derived from agglomerates, tuff and breccias (Berntsen and Rothacher, 1959). Soil infiltration capacities are extremely high and Hortonian overland flow rarely occurs on undisturbed forest floors. As in most areas of the western Cascades the movement of water through the subsurface accounts for nearly all streamflow in undisturbed forest watersheds (Harr, 1977).

The natural vegetation is forest, dominated by Douglas fir *(Pseudotsuga menziesii)* and western hemlock *(Tsuga heterophylla)*. Ages of unmanaged forest stands range from 100 to more than 500 years, reflecting the influence of wildfire. Between 1950 and 1990, 22 percent of Lookout Creek and 25 percent of Blue River were cumulatively harvested in a pattern of dispersed 10 to 20 ha clearcuts accessed by roads. Construction of logging roads began in the mid 1940s in Lookout Creek and in the mid-1950s in Blue River and expanded throughout the following decades (Figure 4). As of 1990, road density in both basins was 1.9 km/km2, and 3 percent of each basin was occupied by roads (Table 1).

### *Estimating Drainage Density Due to Road-Stream Connectivity*

The degree of road-stream connectivity was estimated by surveying road segments and drainage structures on a sample of the road network in the study basins. Calculations of basin area (A), stream network length ($\Sigma L_S$), length of road segments connected to streams ($\Sigma L_{Rc}$), and road segments connected to gullies ($\Sigma L_{Rg}$) were accomplished using a geographic information system (GIS) and field surveys. Drainage density was used as an index to evaluate the potential importance of roads in altering flow-routing efficiency of the basin.

Basin area (A) was calculated by defining basin boundaries from 30-m digital elevation data (DEMs) using Arc/Info GIS software (Environmental Systems Research Institute, Redlands, California). Arc/Info and DEMs also were used to create three GIS layers representing hillslope gradient, basin elevation classes, and hillslope positions. Three hillslope positions were defined: valley bottoms were the area within a 100-m buffer around the fourth- and fifth-order streams; ridgetops were the area within a 100-meter buffer around the boundary of sub-basins > 100 hectares; midslopes were the remaining area. These data layers were subsequently used to develop strata for the field sampling described below.

Because standard topographic maps substantially underestimate the stream network length, we estimated the length of the fully extended stream network ($\Sigma L_S$) by generalizing field-measured maximum channel extents using a GIS algorithm for channel delineation on a DEM. The GIS algorithm available in Arc/Info for channel delineation generates a flow accumulation map 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. Based on a sample of 11 channel heads, we estimated that channel source areas in these basins can be approximated by a constant value, which we set at 2 hectares, roughly the average source area of the sites examined (Figure 5). Other workers have suggested use of an inverse slope drainage-area relationship for estimation of maximum channel extents (Montgomery and Dietrich, 1989). Our observations showed a weak but statistically insignificant relationship between hillslope gradient and drainage area at channel heads (Figure 5), necessitating the use of an average drainage area to estimate maximum network extent.

We estimated the length of the connected road segments ($\Sigma L_{Rc} + \Sigma L_{Rg}$) by using GIS algorithms to determine overall road lengths and lay out a sampling design for a field survey of road-stream connectivity. Road networks (Figure 4) were digitized from 1991 1:100 000 black and white aerial photographs using an analytical stereoplotter and stored as a GIS layer. Each road segment was assigned a decade of construction based on historical maps and aerial photography, and a year of construction corresponding to the year prior to the date of the nearest adjacent clearcut. The length of roads constructed by decade, hillslope gradient, elevation, band, 2nd hillslope position in each basin were calculated by overlaying the road network on each of these layers.

A stratified random sample representing 20 percent of the road network was sampled from July to August 1992 to determine what fraction of the road length routed water to surface flowpaths, namely preexisting stream channels and newly incised gullies below culvert outlets. A total of 31 2-km transects

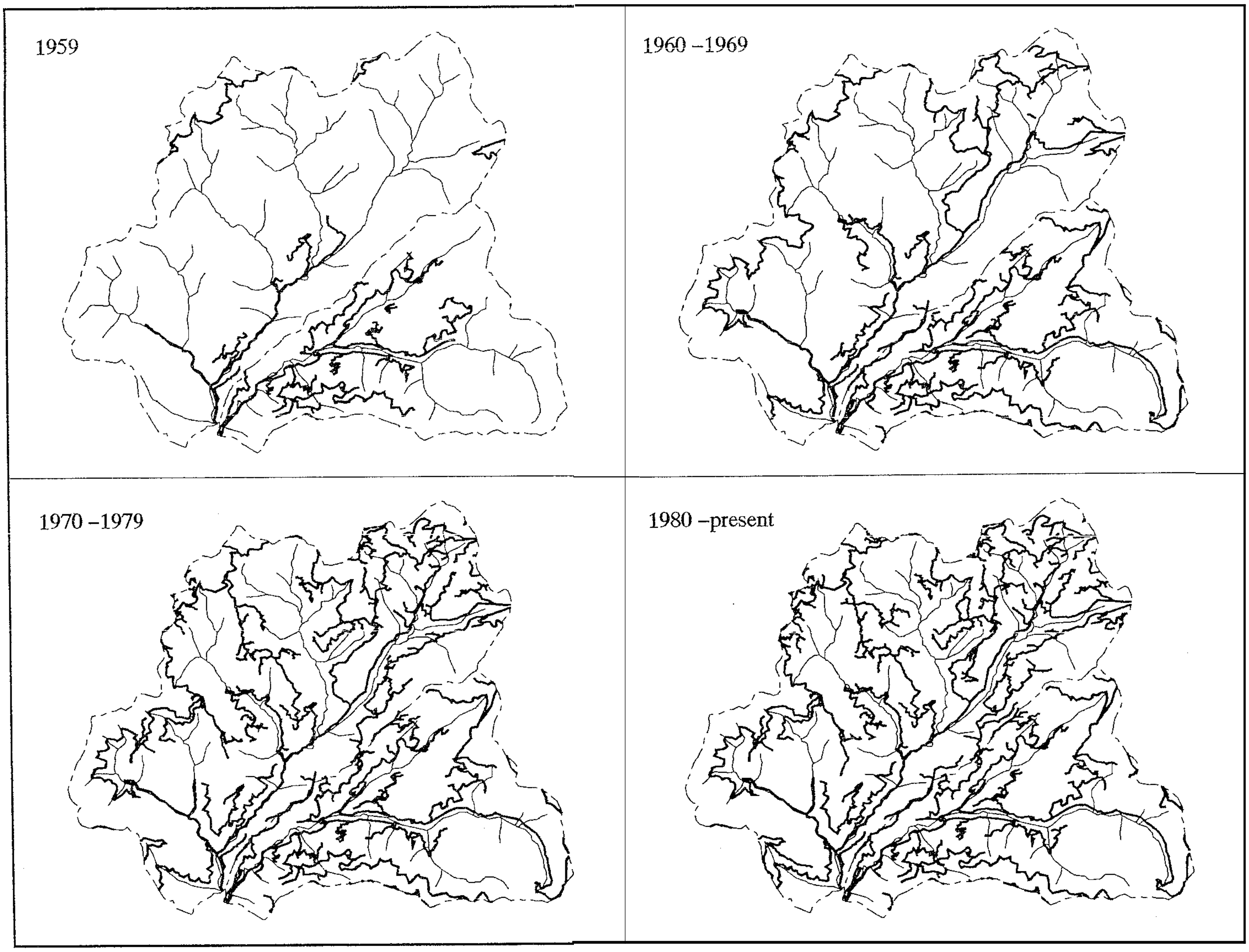

Figure 4. Pattern of Road Network Construction in Lookout Creek and Blue River During Four Decades.

were selected from roads constructed in valley bottom, ridgetop and midslope hillslope positions in each decade between 1950 and 1990 (Figure 3). 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.

Each transect was subdivided into segments demarcated by culverts (Figure 2). For each sampled road segment the following data were recorded: length of road draining to each culvert (L), road grade or average slope of the road draining to each culvert ($\alpha$), average hillslope gradient for the road segment ($\theta$), and the routing of water below the culvert outlet as defined below. The length of each segment was estimated to the nearest 0.01 mile (0.02 km) based on readings from an automobile odometer calibrated with a distance meter with a resolution of 0.01 km. Road grade was measured with a clinometer. Due to difficulties in measuring hillslope gradients under forest cover and distinguishing cut-and-fill slopes from the average hillslope gradient, hillslope gradient was assigned as a categorical variable to each road segment, based on a GIS classification of slopes greater than or less than 40 percent.

Each culvert outlet was classified into one of three categories based on whether its outlet delivered water: (1) directly to a natural stream channel, (2) into a gully incised below the culvert outlet, or (3) onto a hillslope where the water reinfiltrated (Figure 2). Road segments were assigned to category 1 if the culvert was a stream-crossing culvert (which transmits stream water below a road crossing), where a pre-existing channel could be discerned both upslope of the road and below the culvert outlet. Category 1 was also assigned if the ditch-relief culvert outlet was within the bankfull width of the adjacent channel, which occurred in several valley-bottom locations where the road was parallel to the channel. Road segments were assigned to Category 2 if evidence of erosion and formation of a channelized flow path existed for at least 10 meters below the outlet of a ditch-relief culvert. All remaining ditch-relief culverts were assigned to Category *3* (Figure 2).

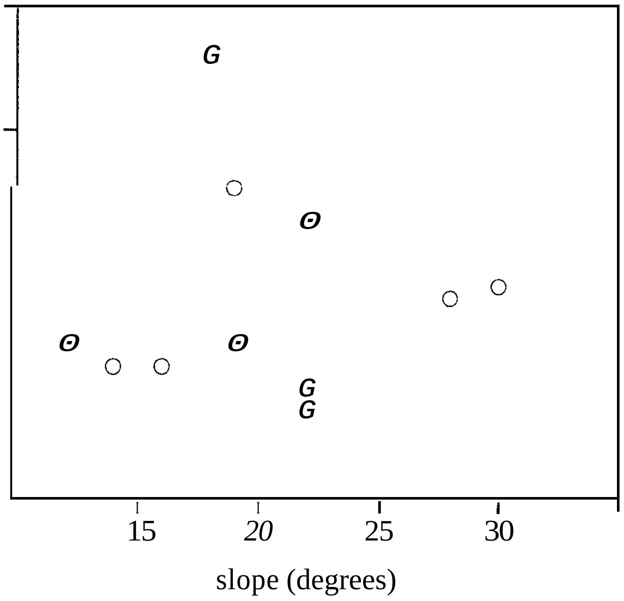

Figure 5. Slope-Drainage Area Relationship for Headwater Streams Mapped in Lookout Creek. No statistically significant relationship is evident for the mapped sites (Y = 0.009X + 1.5, p = 0.87, R2 = 0.33, although there appear to be two marginally significant subgroups of channel heads with drainage areas < 1.1 ha and > 1.6 ha. To delineate the stream network on the digital elevation model, we therefore used a constant source area of slightly less than 2 hectares, roughly approximating the average source area of mapped channels.

Eight randomly selected transects were resurveyed during storm events between January and April 1993 to verify this classification procedure. The resurvey indicated an average classification error of ± 4.6 percent, ? 5.6 percent, and k 7.1 percent for culvert counts in Categories 1,2, and 3.

### *Examining Factors Associated With Gullies*

The sample of 275 ditch-relief culverts from the field survey was examined using a multiple logistic regression (Hosmer and Lemeshow, 1989) to determine whether the occurrence of gullying could be predicted based upon measured characteristics of the road. Eight observations (of 283 ditch-relief culverts discharging to hillslopes, Table 2) were excluded from this analysis due to insufficient data on road grade or hillslope gradient. Models were fitted to predict the occurrence of gullying below ditch-relief culverts (dependent variable) based on: (1)length of road segment (L) draining to the culvert, (2) road grade (a), and *(3)*gradient of the hillslope ($\theta < 40$ percent or $\geq 40$ percent) on which the road segment was located (Figure 2). The final model used road length, hillslope gradient, and their interaction as independent variables.

### *Comparing Roads in Lookout Creek and Blue River*

Observations from field surveys and GIS analyses were compared between Lookout Creek and Blue River. Basin area distributions by elevation and slope were used as a baseline for comparing road development over time. These observations were used to assess the timing and spatial distribution of road development relative to the timing of hydrologic effects associated with forest management observed by Jones 2nd Grant (1996).

## RESULTS AND DISCUSSION

### *Road-Stream Connectivity and Channel Network Extension*

More than 57 percent of the road length surveyed functions as surface flowpaths that are hydrologically connected to the stream network (Table 2). These surface flowpaths are (1) road segments draining to stream channels (34 percent of the 62 km of road surveyed), and (2) road segments draining to culvert outlets with gullies incised below them (24 percent of the surveyed road length) (Figure 2). Of 436 culverts examined, 33 percent (145) were stream-crossing culverts and 23 percent (101) were ditch-relief culverts with gullies incised below the outlet (Table 2).

The fully extended stream channel network has an estimated drainage density in Lookout Creek and Blue River of 3.0 and 2.9 km km-2 without roads, and 4.1 and 4.0 km km-2 with connected road segments

TABLE 2. Characteristics of the Road Drainage System Determined from 31 2-km Transects.

| Culvert Type: | Stream Crossing | Ditch Relief | | | Total |
|---|---|---|---|---|---|
| **Outlet Discharge To:** | Stream' | Stream* | **Gully**** | Subsurface **Flow** | **All** |
| Number of culverts surveyed | 145 | 8 | 101 | 182 | 436 |
| **As** percentage of total culverts surveyed | 33 | 2 | 23 | 42 | 100 |
| **As** percentage of ditch relief culverts | -- | **3** | 35 | 63 | 100 |
| Number of culverts **per** km | 2.3 | 0.1 | 1.6 | 2.9 | 7.0 |
| Total length (km) of surveyed road muted to | 19.8 | | 13.7 | 24.7 | 58.2 |
| Mean percent of surveyed road length muted to | 33.8 | -- | 23.5 | 42.7 | 100 |
| Standard deviation | 18.9 | -- | 13.3 | 19.7 | -- |
| Mean percent of surveyed mad length muted to surface flowpaths (e.g., streams and gullies) | --- | --- | --- | --- | 57.3 |

*Road segments were assigned io Category. 1 if the culvert wasa stream-crossing culvert, or if the ditch-relief culvert outlet was without the bankfull width of the adjacent channel (see text).

**Road segments were assigned to Category 2 if evidence of erosion and formation of a channelized flow path existed for at least 10 meters below the outlet of a ditch-relief culvert.

surveyed in this study. We estimate that connected road lengths increase drainage density by 36 percent and 39 percent in Lookout Creek and Blue River respectively (Table 3). This value is slightly higher if we include an estimate of gully length, based on our field observations (Case *3* in Table 3). The estimated increase in drainage density is rather sensitive to assumptions about the length of the pre-existing stream network and which road segments may truly be considered connected to streams. If only stream crossings are considered as true road-stream connections (Case 1 in Table 2), the estimated increase in drainage density is as low as 21 and 23 percent in Lookout Creek and Blue River. An increase in drainage density of about 50 percent (Case 4 in Table 2) results if the estimated stream length is approximately equal to the winter baseflow stream network in Lookout Creek (e.g., *75* percent less than our extended stream network, after Wemple, 1994). These sensitivity tests on the extent of drainage density change indicate the dynamic nature of road-stream connections. Hydrologic integration of portions of the road network in response to expansion and contraction of the stream network may be best thought of as varying dynamically in space throughout a season.

### *Gully Formation*

Gullies formed below culvert outlets are a form of road-stream connectivity quite different from roadside ditches. During large storm events when soils are saturated and the stream network is fully extended, gullies appear to function as channels or discontinuous surface flowpaths similar to several of the first-order channels we surveyed (e.g., Figure 5). Of the 120 culverts that were resurveyed during storm events in the winter of 1993, 25 percent (30 culvert outlets) were classified as gullies because they emptied into a channelized flowpath carrying surface runoff that was not a pre-existing stream (Figure 2). Fourteen of these flowpaths conveyed surface runoff to a channel or saturated area at a distance no greater than 20 meters downslope of the culvert outlet. Sixteen of these features functioned as discontinuous surface flowpaths.

Gullies may be formed by chronic channel incision from concentrated surface flow, or by episodic mass movements, or both. Road length draining to the culvert and road grade alone, typically used in design procedures for culvert spacing, did not adequately predict the occurrence of gullying ($\chi^2 = 3.48$ with 3 degrees of freedom; $p = 0.25$). A logistic regression model including length of road segment, hillslope gradient, and their interaction accurately predicted the occurrence of gullying below culverts in Lookout Creek and Blue River in 184 of 275 cases (67 percent of cases) ($\chi^2 = 29.29$ with 4 degrees of freedom; $p < 0.01$). At any given road length, the odds of gullying are substantially higher on steep ($\geq$ 40 percent) slopes than on gentle (< 40 percent) slopes. In addition, the odds of gullying on steep slopes increases with increasing length of road draining to a culvert, while

TABLE 3. Estimated Changes in Drainage Density Based on Connected Road Length in Lookout Creek and Blue River Under Four Sets of Assumptions.

| | Stream Crossings **Only**[1] | | Stream Crossings and Ditch Relief Culverts[2] | | Stream Crossings Ditch-Relief Culverts and Gullies[3] | | Stream Crossings Ditch-Relief Culverts, **>2 ha** Stream Network[4] | |
|---|---|---|---|---|---|---|---|---|
| | Lookout Creek | **Blue** River | Lookout Creek | Blue River | Lookout Creek | Blue River | Lookout Creek | Blue River |
| 1. Stream length (km) | 189 | 341 | 189 | 341 | 189 | 341 | 142 | 256 |
| 2. Drainage density without roads ($km/km^2$) | 3.0 | 2.9 | 3.0 | 2.9 | 3.0 | 2.9 | 2.3 | 2.2 |
| 3. Road length connected to surface flowpaths (km) | 40 | 78 | 68 | 132 | 68 | 132 | 68 | 132 |
| **4.** Effective drainage length (km) | 229 | 419 | 257 | 473 | 261 | 482 | 210 | 388 |
| 5. Drainage density with roads ($km/km^2$) | 3.7 | 3.5 | 4.1 | 4.0 | 4.2 | 4.1 | 3.4 | 3.3 |
| **6.** Change in drainage density (percent) | 21 | 23 | 36 | 39 | 40 | 41 | 48 | 50 |

[1] Assumes only road ditches draining to stream-crossing culverts (33.8 percent of total road length, based on field survey) are connected (effective drainage length = $\Sigma L_S + \Sigma L_{Rc}$).

[2] Assumes road ditches draining to stream-crossing culverts and road ditches draining to ditch-relief culverts with gullies (23.5 percent of total road length) are connected (effective drainage length = $\Sigma L_S + \Sigma L_{Rc} + \Sigma L_{Rg}$).

[3] Assumes road ditches draining to stream-crossing culverts, road ditches draining to ditch-relief culverts with gullies, and the gullies themselves are connected (effective drainage length = $\Sigma L_S + \Sigma L_{Rc} + \Sigma L_{Rg} + \Sigma L_G$). The $\Sigma L_G$ was calculated assuming seven culverts $km^{-1}$ of road *25 percent of culverts with gullies *20 m of gully length per gullied culvert = 0.0375 km of gully length $km^{-1}$ of road.

*Assumes road ditches draining to stream-crossing culverts and road ditches draining to ditch-relief culverts with gullies are connected, hut stream network is shorter by 25 percent than estimated using the 2-ha source area.

on slopes less than 40 percent the odds of gullying is approximately constant over the range of road lengths surveyed (Figure 6) (Hosmer and Lemeshow, 1989).

Episodic mass failures (debris slides) at culvert outlets are a related mechanism by which road segments become connected to streams. Swanson and Dyrness (1975) had previously identified debris slides resulting from road fill slope failures at seventeen culvert locations included in this field survey. In our independent assessment of these locations in 1992 (Wemple, 1994), ten were classified as gullies, and four were classified as stream channels. This form of permanent road-related stream network extension might result from road drainage failures that produce saturation and subsequent failure of the road fill, particularly during extreme high-rainfall events such as the storms of December 22, 1964, and February 7, 1996 (F. J. Swanson, personal communication).

### *Relationship to Observed Changes in Peak Flow Behavior*

Changes over time in the length of road connected to the stream network are consistent with the timing of observed increases in peak flows in Lookout Creek and Blue River noted by Jones and Grant (1996). The present distribution of roads in Lookout Creek and Blue River is similar with respect to slope angle and elevation (Figure 7). However, the major period of road construction and harvesting occurred 15 years later in Blue River than in Lookout Creek (Figure 8); 85 percent of existing roads in Lookout Creek had been constructed by 1965, whereas 85 percent of existing roads had been constructed by 1980 in Blue River. Jones and Grant (1996) noted that unit area peak flows were significantly higher in Lookout Creek than Blue River in the 1960s, but significantly higher in Blue River relative to Lookout Creek in the 1970s and 1980s. They offer several possible explanations for observed peak flow changes, including the hypothesis that road ditches might capture increased subsurface flow downslope of clearcuts and route it as surface flow to streams. The extent of road-stream connectivity noted in this study and the magnitude of drainage-density increases attributable to roads support, this hypothesis and provide one possible explanatory mechanism (e.g., enhanced routing efficiency) for observed changes in peak flows.

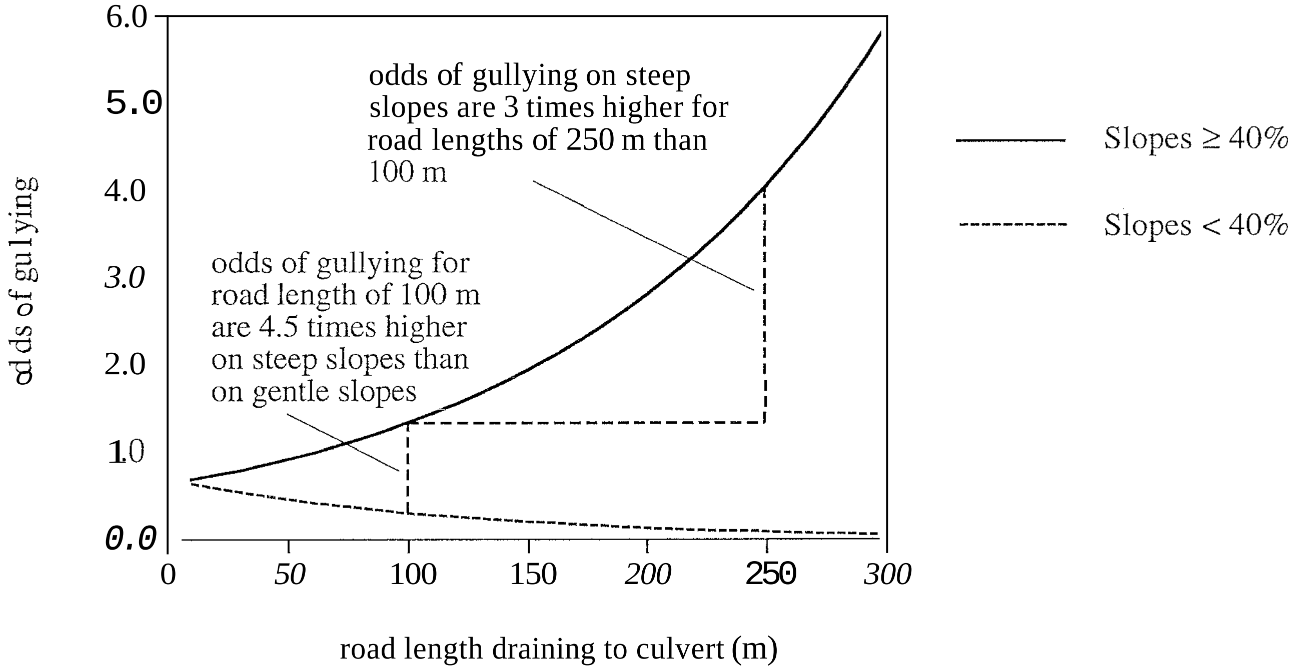

Figure **6.** Relationship Between the Odds for the Occurrence of a Gully Below Ditch Relief Culverts Against Road Length. The logistic regression equation for the relation between the occurrence of gullying and road length (in meters), hillslope gradient (1 for slopes < 40 percent, 0 for slopes ≥ 40 percent), and the interaction of these two variables is given by odds = exp [-0.4522 + (0.0074 x length) + (0.0810 x slope) - (0.0156 x length x slope)] (Hosmer and Lemeshow, 1989). At **a** road length (e.g., culvert spacing) of 100 meters, gullies are 4.5 times more likely to occur on steep (≥ 40 percent) than on gentle (< 40 percent) slopes (odds ratio for steep vs. gentle slopes at 100 meters = 1.34/0.30). Steep slopes show increased odds of gullying with increasing road length, for example gullies are roughly three times as likely to occur on steep slopes as road length increases from 100 to 250 meters (odds ratio for 250 m vs. 100 m road length on steep slopes = 4.07/1.34).

### *Conversion of Subsurface Drainage to Quickflow*

Following our conceptual model (Figure 1), the hydrologic impact of roads depends upon the extent to which roads contribute to the volume of rapid surface runoff in a basin. We observed several road segments carrying unit area discharges as high as those of the larger basins to which they contribute. A discharge of 1.18 L/s was measured from an estimated 2-ha drainage area on a Lookout Creek road ditch during a storm on March 19, 1993, representing only 20 percent of the basin-wide unit area discharge for Lookout Creek on this date (3.21 L/s/ha). However, on June 9, 1993, a discharge of 7.3 L/s was measured from an estimated 10-ha drainage area on a Blue River road ditch, representing roughly 100 percent of the unit-area basin discharge on this date (0.652 L/s/ha).

We expect that hillslope position affects a road segment's ability to convert subsurface water to surface runoff. Connected ditch segments along midslope roads are more likely than those along ridgetop or valley bottom roads to intercept significant amounts of subsurface flow and convert it to surface runoff (e.g., Megahan, 1972). Ridgetop roads may lower the threshold for channel initiation (Montgomery, 1994), but road segments along ridgetop roads may not intercept subsurface flow because of their small contributing drainage areas. Valley bottom roads frequently have culverts discharging directly to streams but are relatively ineffective at diverting subsurface water to surface runoff (Wright et al., 1990). Differences in the effectiveness of roads in capturing subsurface water and the routing of water via surface flowpaths associated with roads may explain some of the variability in results of small-basin experiments investigating road effects on basin hydrology.

### *Generalization of Study Results Using GIS*

This study made extensive use of a geographic information system to select sites for sampling and to generalize results to the basins studied. GIS layers were overlaid to develop the sampling design for the field survey of roads. Algorithms provided in the GIS software were coupled with field observations to generate a map of the extended stream network that

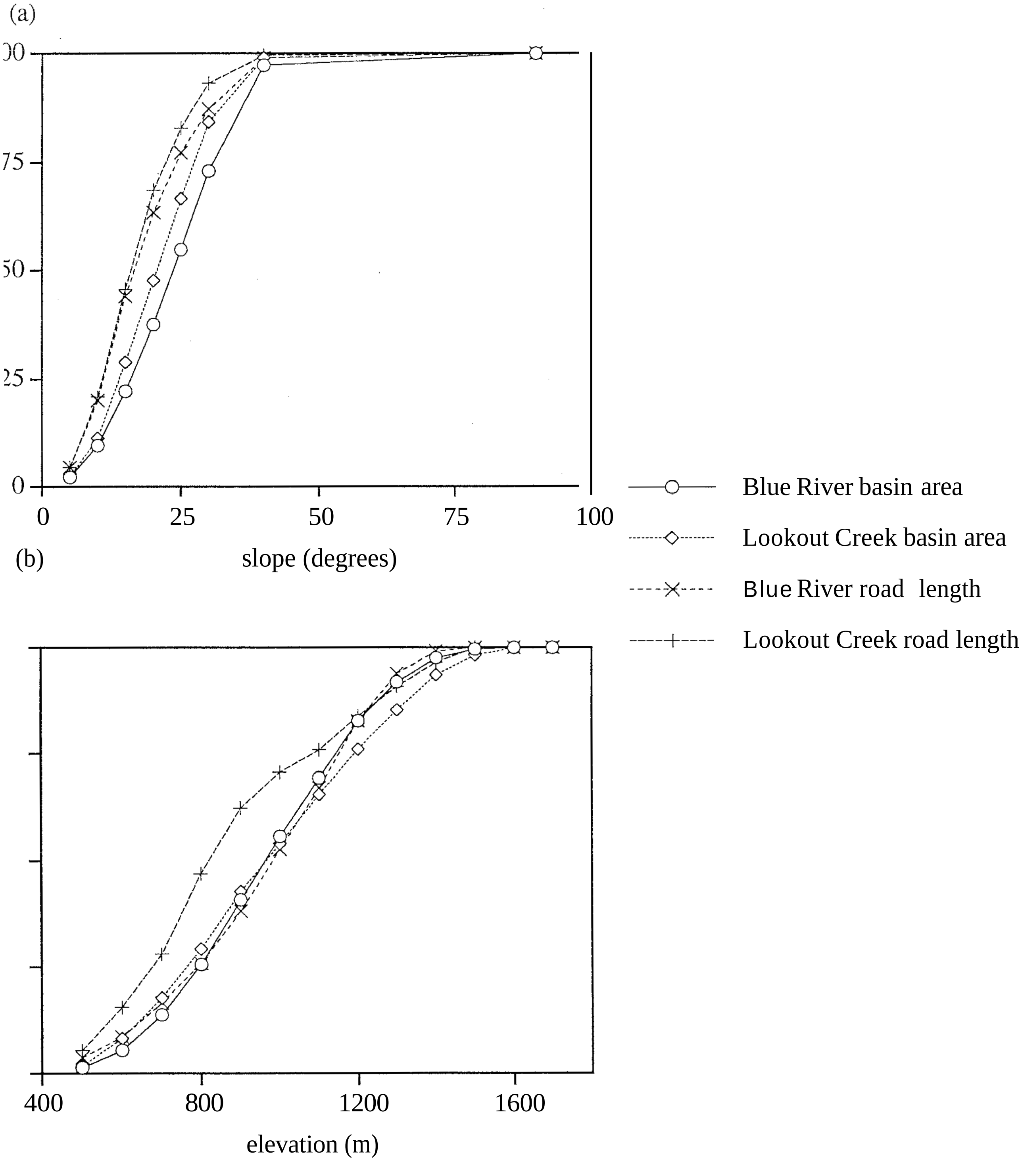

Figure 7. Road Network and Basin Area Oistribution With Respect to Slope and Elevation in Lookout Creek and Blue River. Despite similar distributions of basin area by elevation, a greater percentage (50 percent) of Lookout Creek mads lie in lower elevations (below 800 m), compared to 30 percent of Blue River roads. This pattern reflects the trend in recent decades toward road construction on upper hillslopes and ridges.

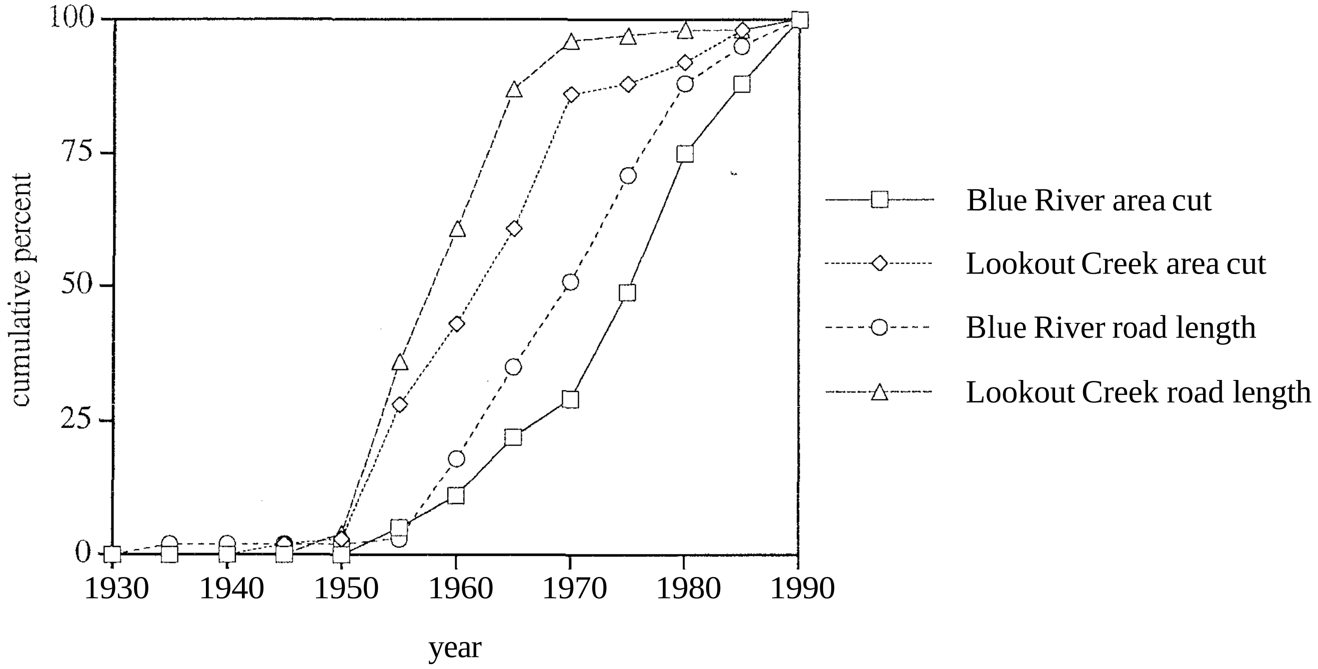

Figure 8. Cumulative Length of Road Constructed and Harvest Units Cut Over Time in Lookout Creek and Blue River.

was used as a baseline against which to estimate the increase in drainage density attributable to roads. A GIS layer of hillslope gradient was used as an input variable for the regression analysis of factors controlling gullying. Finally, GIS algorithms were used to create maps illustrating the spatial distribution of road-stream connectivity (e.g., FEMAT, 1993, p. V-21).

## CONCLUSIONS

The most important findings of this study are (1) a large proportion (57 percent) of the road network in the basins studied is hydrologically connected to the stream network; (2) enhanced routing efficiency, (indexed here as an increase in drainage density) due to connected road segments provides a possible explanatory mechanism for changes in hydrograph shape following road construction (e.g., Jones and Grant, 1996); and (3) the timing of road development and accompanying hydrologic integration of the road network corresponds to the timing of observed changes in peak flows in Lookout Creek and Blue River, as noted by Jones and Grant (1996). This finding is specific to the road-stream system we examined: up to 40-year-old cut-and-fill roads constructed at all hillslope positions on moderately stable to unstable soils with high moisture storage capacity and percolation rates. While this work does not prove that roads cause increases in peak flows, it supports the hypothesis that road segments linked to the channel network increase flow routing efficiency and hence provides a plausible mechanism for observed increases in peak flows.

The conceptual model presented in this study outlines a general approach for assessing the magnitude of road hydrologic effects. Our examination of channel extension by roads represents one step toward a quantitative estimate of the extent of road impacts on basin hydrology. The index of drainage density serves only as a metric for the extent to which surface flowpath lengths are increased due to roads. The index cannot be directly related to changes in the size of peak flows (e.g., Carlston, 1963) without further understanding of the mechanisms controlling surface runoff generation on roads. The volumes of water captured by roads and the extent to which roads effectively truncate subsurface flowpaths are important elements of our conceptual model and the subject of on-going research.

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