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Road surface drainage, channel initiation, and slope instability

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Abstract. Field surveys of road drainage concentration at three sites in the western United States are used to test simple models relating channel initiation and shallow landsliding to ground slope and contributing area thresholds. The form of boundaries between data for locations where road drainage concentration is associated with either shallow landsliding, channel initiation by overland flow, or no observable geomorphic effect is consistent with theoretically derived drainage area–slope relations. Comparison of survey data with results of previous studies in these areas indicates that the drainage area required to support a channel head is smaller for road-related runoff than for undisturbed slopes. Contrary to current land management paradigms in the Pacific Northwest, drainage concentration from ridgetop roads may cause both landsliding and integration of the channel and road networks. Road drainage concentration increases the effective length of the channel network and strongly influences the distribution of erosional processes in each of the study areas. The approach of using field reconnaissance to establish thresholds for erosion associated with road drainage provides a useful method to define regional criteria for road design that should reduce impacts on downstream channel systems.

Introduction

Road building results in a wide variety of environmental impacts. Although virtually all road surfaces alter both drainage patterns and runoff generation, the geomorphic impact of road construction has received little attention in a quantitative theoretical framework. Significant road-related geomorphic impacts include (1) destabilization of side-cast material and hillsides downslope (Figure 1); (2) gullying and channel network expansion; (3) increased downstream sediment loads; and (4) altered streamflow and channel adjustments (see *Megahan* [1987] and *Furniss et al.* [1991] for recent reviews). Many previous workers established, for example, that erosion rates from road surfaces and road-related landslides are many times greater than from undisturbed slopes [e.g., *Megahan and Kidd*, 1972; *Swanson and Dyrness*, 1975; *Beschta*, 1978; *Rice et al.*, 1979; *Dunne and Dietrich*, 1982; *McCashion and Rice*, 1983; *Reid and Dunne*, 1984; *Schroeder and Brown*, 1984; *Amaranthus et al.*, 1985; *Anderson and Potts*, 1987]. Road-related impacts generally result from concentration of both runoff generated on road surfaces and intercepted subsurface discharge. Concentration of road drainage can have various geomorphic effects: (1) increased discharge may have no identifiable geomorphic impact, (2) the discharge increase may be sufficient to initiate or enlarge a channel, or (3) the concentrated discharge may contribute to slope instability below the drainage outfall. This paper compares models for erosion initiation by overland flow and shallow landsliding with data from field surveys of road drainage concentration in three study areas in the western United States.

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Theory

Differences in runoff generation from road surfaces and natural slopes are well known. Relatively impermeable road surfaces are a source of rapid runoff, which increases both peak rates and volumes of runoff [e.g., *Megahan*, 1972; *Harr et al.*, 1975; *King and Tennyson*, 1984]. Roadside ditches also intercept both surface and shallow subsurface runoff from upslope areas and route the accumulated discharge to culverts or other locations [e.g., *Burroughs et al.*, 1972; *Megahan*, 1972; *King and Tennyson*, 1984]. Such drainage alterations and diversions may alter channel network pattern, extent, and processes.

Threshold theories for channel initiation and slope instability [e.g., *Horton*, 1945; *Schaefer*, 1979; *Dietrich et al.*, 1986, 1992, 1993; *Montgomery and Dietrich*, 1989, 1994a; *Willgoose et al.*, 1991] provide a context within which to analyze erosional impacts of drainage modification. The essential principle underlying these theories is that erosion occurs once surface or subsurface discharge overcomes the erosional resistance of the ground. Many factors influence the specific timing and location of erosion, including the intensity and duration of rainfall and temporal variations in the contribution of vegetation to soil strength. Threshold models for the spatial distribution of erosional processes, however, may be developed in terms of drainage area, ground slope, and soil properties (e.g., critical shear stress, bulk density, and friction angle).

Erosion by overland flow and shallow landsliding are common channel initiation mechanisms in humid, soil-mantled landscapes. Each of the following models for erosion initiation by these mechanisms assumes a steady state rainfall and spatially uniform soil properties to relate the critical drainage area per unit contour length (a_{cr}) to local ground slope ($\tan\theta$). The steady state assumption limits these models to predicting the form of the relation between a_{cr} and $\tan\theta$.

The overland flow model considers a critical shear stress

Figure 1. Road-related landsliding in the central Washington Cascades.

(τ_{cr}) to control channel initiation. *Montgomery and Dietrich* [1994a] derived expressions for a_{cr} under both laminar flow

$$a_{cr} = \frac{2(\tau_{cr})^3}{qk\nu\rho_w^3 g^2(\sin\theta)^2} \tag{1}$$

and turbulent flow

$$a_{cr} = \frac{(\tau_{cr})^{5/3}}{q(\rho_w g)^{5/3} n(\sin\theta)^{7/6}} \tag{2}$$

where q is the rainfall rate in excess of the infiltration capacity of the surface generating runoff, k is a dimensionless surface roughness coefficient, ν is the kinematic viscosity of water, ρ_w is the density of water, g is gravitational acceleration, and n is Manning's roughness coefficient. Each of these equations predicts an inverse critical area-slope relation; a greater drainage area is required to initiate a channel on a gentler slope. Furthermore, since road construction generates a topographic surface with a decreased infiltration capacity, (1) and (2) predict that channel initiation by runoff generated on road surfaces requires smaller drainage areas than for undisturbed ground.

While Hortonian overland flow occurs only rarely on soil-mantled hillslopes in humid regions [*Dunne*, 1978], it is the dominant runoff mechanism for road surfaces. Discharge intercepted by roads, however, may be better modeled using the analogous model for laminar saturation overland flow [*Dietrich et al.*, 1993]:

$$a_{cr} = \frac{2(\tau_{cr})^3}{qk\nu\rho_w^3 g^2(\sin\theta)^2} + (T/q)\sin\theta \tag{3}$$

where T is the transmissivity of the saturated soil. Rainfall rates typically are less than infiltration capacities for landscapes that generate saturation overland flow [*Dunne*, 1978]. In this case, q is simply the rainfall rate.

Analogous topographic controls on shallow landsliding may be developed through coupling simple hydrologic and slope stability models [see *Montgomery and Dietrich*, 1989, 1994a, b; *Dietrich et al.*, 1993]. The coupled model essentially relies on an expression for the convergence of shallow through-flow to predict the proportion of the soil thickness that is saturated, which is then input into the infinite-slope stability model. Following *Dietrich et al.* [1993], the model assumes infiltration of steady state rainfall and runoff by shallow subsurface flow through cohesionless soil overlying less conductive bedrock. For cohesionless soils the critical drainage area per unit contour length required to initiate a shallow landslide is given by

$$a_{cr} = (T/q)\sin\theta\,(\rho_s/\rho_w)[1 - (\tan\theta/\tan\phi)] \tag{4}$$

where ρ_s is the soil bulk density and ϕ is the friction angle of the soil. The implicit assumption of slope parallel flow precludes consideration of pore pressures greater than hydrostatic. Thus (4) is only valid for steep slopes where $\tan\theta \geq [(\rho_s - \rho_w)/\rho_s]\tan\phi$, a condition that generally can be approximated by $\tan\theta > 0.5$.

Equations (1)–(4) predict different drainage area–slope relations for channel or landslide initiation. Comparison of field-mapped channel networks in natural landscapes (i.e., no road drainage influence) with topographic thresholds defined using digital elevation models indicates that such thresholds can be used to define drainage area–slope relations below which channels do not develop [*Montgomery and Dietrich*, 1992]. Derivations of these models and more detailed discussions of their assumptions and limitations are presented elsewhere [*Montgomery and Dietrich*, 1989, 1994a, b; *Dietrich et al.*, 1992, 1993].

Study Areas and Methods

Road alignments and drainage patterns were mapped onto topographic maps in three study areas in the western United States: near Oiler Peak in the southern Sierra Nevada, California; on Mettman Ridge in the Oregon Coast Range; and along Huelsdonk Ridge on the Olympic Peninsula, Washington (Figure 2). Previous field mapping of channel network extent in portions of the southern Sierra and Mettman Ridge study areas that are uninfluenced by road drainage documented drainage area–slope thresholds that define channeled and unchanneled portions of the landscape [*Montgomery and Dietrich*, 1988, 1992]. Road drainage patterns and the associated drainage diversions were mapped in the field. Discharge points were identified as locations where (1)

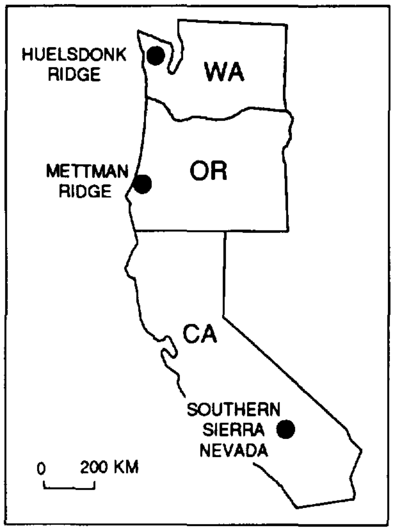

Figure 2. Location map for the study areas.

flow was directed from the road surface either onto a hillside or into a channel, (2) roadside ditches delivered flow to culverts, or (3) road surface drainage ponded and spilled over road margins and onto hillsides. In each study area, average ground slopes were measured in the field over a distance of about 5 m downslope from locations where road drainage was concentrated. Drainage areas were determined differently in each study area, as discussed further below.

Mapping road drainage and determining contributing areas are subject to error because of uncertainty associated with partitioning road surface runoff between different potential discharge points. L. Reid (personal communication, 1993), for example, estimated that surface mapping of road drainage was accurate to about ±30% of the actual contributing area when conducted at times when runoff was not occurring. She also found that mapping road surface drainage patterns during or immediately after runoff-producing events improved the accuracy of contributing area estimates to about ±10%.

Southern Sierra Nevada, California

The drainage system associated with a paved two-lane highway near Oiler Peak provides an example of the effects of road drainage diversions on gully development and channel network expansion. The area is underlain by deeply weathered granitic rocks with thick (i.e., >2 m) colluvial soils developed in topographic hollows. Most slopes in this area are gentle (i.e., $\tan \theta < 0.5$), and vegetation consists of open oak forest and grasslands. The road system is located approximately halfway downslope from the drainage divide to natural channel head locations. Road cuts truncate colluvial fills in topographic hollows and weathered bedrock in noses and divert both surface and subsurface flow into an in-board ditch system that drains through culverts into valley bottoms.

Roadside ditches contributing runoff to culverts were mapped along a 2-km stretch of road. Identification of drainage diversions was based on delineating the upslope drainage areas contributing runoff to roadside ditches and assuming that the runoff from these areas is delivered to culverts. Drainage areas both prior and subsequent to road construction then were determined from the mapped pattern of drainage diversions.

At each of the culvert outfalls, road drainage concentration has integrated the road and channel networks, allowing the road surface to act as an extension of the channel network. Within the area shown in Figure 3, four hollows (A, C, E, and G) lost drainage area through drainage diversions. In each of these cases the channel begins significantly downslope of the road. In contrast, three hollows (B, D, and F) receive additional drainage from the road system and the channels begin at or immediately downslope of culverts. In the area shown, 570 m of the road drainage network is integrated with channels, increasing the effective drainage density (here used in the sense of the channel density of *Montgomery and Dietrich* [1994a]) by a factor of 1.67, or from 5.2 to 8.7 km^{-1}. For the whole 1.2-km^2 basin in which the extent of the channel network was mapped, integration of the road and channel networks increased the drainage density by a factor of 1.6, or from 2.8 to 4.4 km^{-1}. These minimum estimates of the increase in drainage density neglect the length of any new channels incised between culverts and previous channel heads.

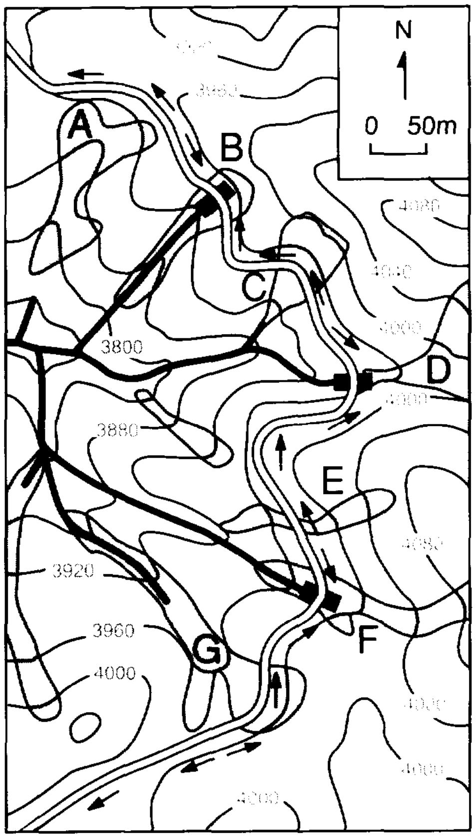

Figure 3. Map of a portion of the southern Sierra Nevada study site; channels represented by thick lines, colluvial deposits in topographic hollows by shading, and road drainage by arrows. Contour interval is in feet (1 foot equals 0.3048 m). Culverts indicated by solid boxes.

In addition to redistributing discharge, road drainage influences the threshold for channel initiation in this area. While the transition from channeled to unchanneled slopes exhibits the same inverse form for both natural and road-altered drainage (Figures 4a and 4b), less drainage area appears to be required to initiate a channel for hollows receiving road drainage (Figure 4c). A test for the equivalence of the regressions [*Berenson et al.*, 1983] of log area on log slope for each of the two data sets shown in Figure 4c allows rejection at the 0.05 significance level of the hypothesis that the two data sets are drawn from the same population. The similar form (i.e., slope) to the lower bound of the unchanneled data, however, implies that road drainage has not altered the dominant channel initiation process.

Huelsdonk Ridge, Washington

Recently constructed logging roads on Huelsdonk Ridge provide an example of the effect of ridgetop road drainage on channel network extension and slope stability. Steep clear-cut slopes drain to narrow tributary channels that empty into a wide alluviated valley along the South Fork Hoh River. Most shallow landslides in this area originate in topographic hollows, and landslide inventories from historical aerial photographs indicate that the rate of landslide initiation increased dramatically following road construction and clear-cutting [*Schlichte*, 1991].

A 7.8-km stretch of the gravel road system along Huels-

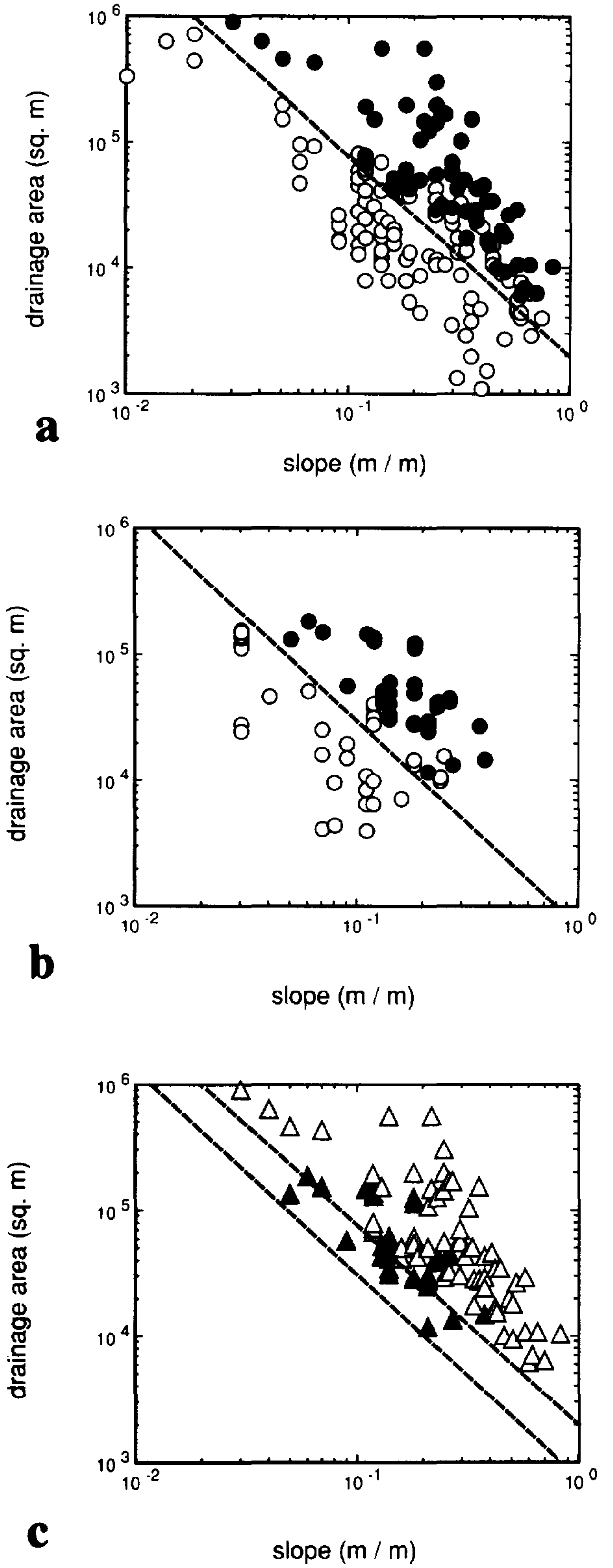

Figure 4. (a) Plot of drainage area versus local slope for channeled (solid circles) and unchanneled locations (open circles) in the southern Sierra Nevada study site for natural drainage. (b) Same as Figure 4a for road-related drainage diversions. (c) Similar plot showing only channeled data for natural drainage (open triangles) and road-related drainage (solid triangles). Dashed lines are approximate thresholds defining the lower bound to channeled data.

donk Ridge was mapped onto a 1:4800 scale topographic map. Road drainage divides, culverts, and other locations where road drainage discharged onto the slopes were mapped. Road surface widths measured in the field consistently were 5.6 m. As is typical throughout the Pacific Northwest, ridgetop road drainage generally is focused into the heads of topographic hollows (Figure 5). Each discharge point was classified as either not influencing erosion, causing channel formation immediately downslope, or producing a shallow landslide scar. The Huelsdonk Ridge survey was conducted during the summer, and drainage areas contributing to each location where road drainage was concentrated were calculated as the product of the contributing road length and the road width; diversion of upslope drainage was minimal because of the ridgetop location.

Data from these classes appear to define distinct fields on a plot of drainage area versus slope (Figure 6). Data from locations where road drainage does not influence downslope erosion (unchanneled) plot at the lowest drainage areas and slopes. Data from locations where road drainage initiates a channel (channeled) plot at higher drainage areas. Road drainage–associated landslides plot at the highest drainage areas and steepest slopes. Although the sample sizes are small, the significance of this interpretation is supported by Kolmogorov-Smirnov tests [*Sprent*, 1989] of the null hypothesis that each population (unchanneled, channeled, and landslide) of the variables (drainage area and slope) are drawn from identical distributions (Table 1). Unchanneled sites appear to have significantly smaller drainage areas than either channeled or landslide sites; landslide sites appear to be steeper than channeled sites.

These data also are consistent with the form of relations predicted by (2) and (4) (Figure 6). Channeled and unchanneled data are reasonably segregated by

$$A = 400 \text{ m}^2/\sin\theta \qquad (5)$$

a relation similar to the form predicted for channel initiation by turbulent overland flow, such as might be expected where road drainage is discharged onto natural slopes. Using estimates of $T = 65$ m^2/d, $\rho_s = 1800$ kg/m^3, and $\phi = 45°$ [*Montgomery and Dietrich*, 1994b] and varying the steady

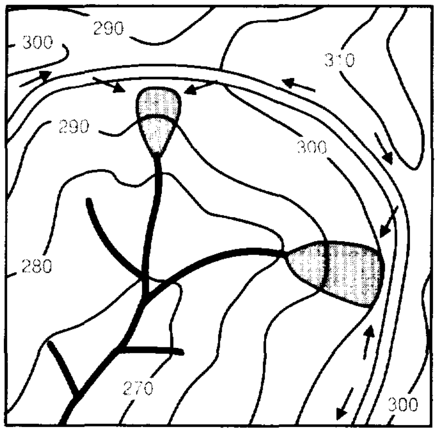

Figure 5. Schematic illustration of ridgetop road drainage concentration into topographic hollows. Landslides represented by shading, channels by thick lines. Modified from a sketch by W. E. Dietrich.

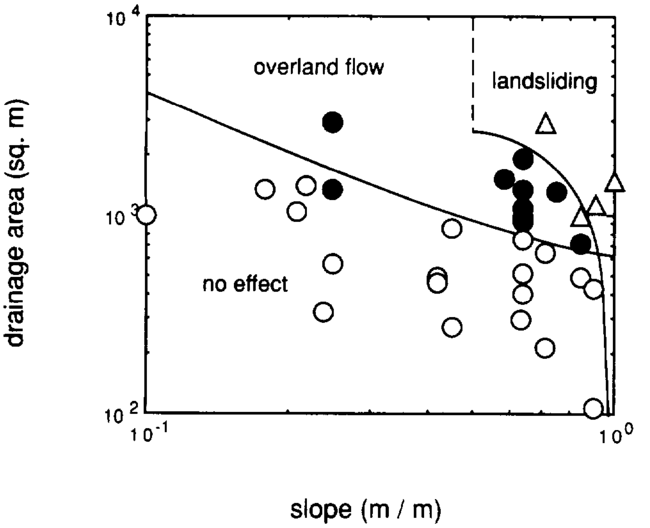

Figure 6. Contributing road drainage area versus slope at the discharge point for the ridgetop road system on Huelsdonk Ridge. Locations immediately downslope of the discharge point were either unchanneled (open circles), channeled (solid circles), or a shallow landslide scar (triangles). Lines indicate fitted form of models for turbulent overland flow and for landsliding; dashed vertical line indicates lower-gradient limit to applicability of landslide model.

state rainfall q in (4), I calculated a lower bound to landsliding (curved line) that fits the observed data well.

Mettman Ridge, Oregon

The forest road system on Mettman Ridge provides another example of the effect of ridgetop road drainage on erosional processes. The gravel road system is located along narrow ridge crests separating steep slopes, which are divided by regularly spaced hollows that indent ridgetop drainage divides. At many locations, road drainage is discharged into the heads of topographic hollows. Road surface widths measured in the field consistently were 3.5 m. Landslides are a major channel initiation mechanism in this area [*Montgomery and Dietrich*, 1988], and landslide-related sediment transport accelerated dramatically after road building and forest clearance, with most of the increase coming from failures associated with road drainage concentration or logging landings [*Montgomery*, 1991].

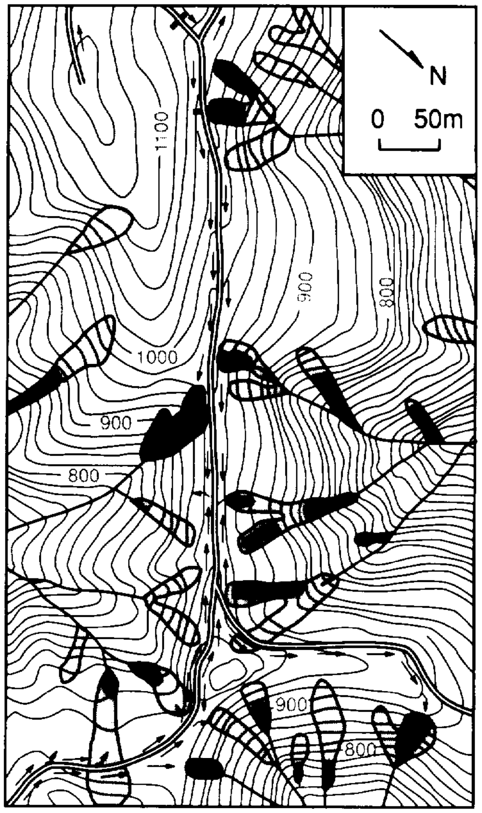

Figure 7. Map of a portion of the Mettman Ridge study area showing road drainage patterns, landsliding (solid areas), channels (thick lines), and colluvial deposits (shaded areas). Contour interval is in feet.

A total of 3.2 km of the gravel road system was mapped onto 1:4800 scale topographic maps (Figure 7). Road drainage flow directions, drainage divides, culverts, and other points of drainage concentration were mapped immediately after rainfall that produced copious runoff from road surfaces. In a number of cases, distinct channels on either side of the road crown drained to opposite sides of a ridge. Moreover, flow down the road surface sometimes bypassed culverts. These and other observations were used to allocate road surface area to each discharge point; upslope drainage diversions were minimal along this ridgetop road. Each discharge point was classified according to its association with either (1) no apparent geomorphic effect, (2) channel incision by overland flow, or (3) shallow landslide scars. Integration of the ridgetop road network with the channel network in the three Mettman Ridge basins mapped in my previous studies would increase the drainage density by a factor of 1.23, or from 9.9 to 12.2 km^{-1}.

Table 1. Results of Kolmogorov-Smirnov Tests for Huelsdonk Ridge Data

	Channeled Versus Unchanneled	Unchanneled Versus Landslide	Channeled Versus Landside
Area	differ	differ	same
Slope	same	same	differ

Paired slope and area distributions were tested against the null hypothesis that the distributions are the same at the 0.05 significance level.

Data from Mettman Ridge exhibit general relations similar to the Huelsdonk Ridge data (Figure 8). Locations where drainage concentration has no observable geomorphic effect plot at the smallest drainage areas and slopes. Locations where road drainage initiates a channel plot at higher drainage areas and slopes, while those locations where road drainage is associated with landsliding plot at the highest drainage areas and are restricted to steep slopes (i.e., tan $\theta > 0.5$). Again sample sizes are small, but these interpretations are supported by Kolmogorov-Smirnov tests [*Sprent*, 1989] of the null hypothesis that each of the variables are drawn from populations with identical distributions (Table 2). Although not particularly powerful, these tests imply that unchanneled sites have smaller drainage areas than channeled or landslide sites and that the population of landslide

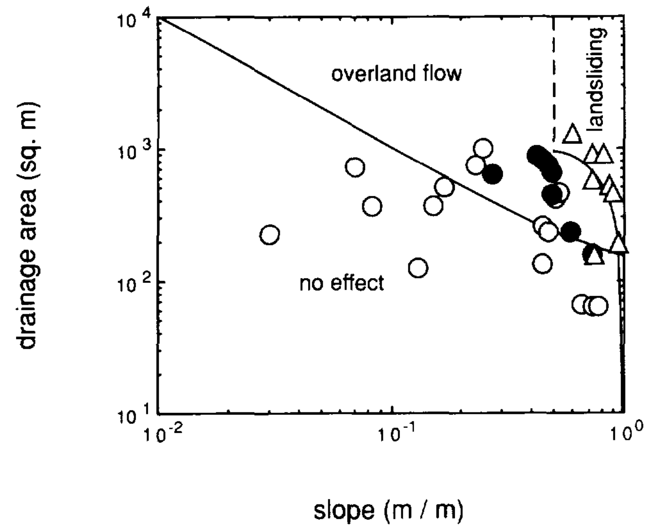

Figure 8. Plot of contributing road drainage area versus local slope at discharge points for ridgetop roads in the Mettman Ridge study area for unchanneled locations (open circles), channels extending to the drainage outfall (solid circles), and landslides immediately downslope of the drainage outfall (triangles). Lines indicate fitted models for channel initiation by overland flow and landsliding; dashed vertical line indicates lower-gradient limit to applicability of landslide model.

sites is steeper than those for both channeled and unchanneled sites.

Equations (2) and (4) also provide reasonable boundaries to unchanneled, channeled, and landslide data from the Mettman Ridge road drainage survey (Figure 8). The lower bound to the data from channeled road drainage locations along Mettman Ridge can be approximated by

$$A = 100 \text{ m}^2/\sin\theta \qquad (6)$$

This is significantly lower than for the Huelsdonk Ridge data, presumably reflecting differences in climate and soil properties between these study areas. This difference illustrates that a single relation is not applicable to all landscapes. Appropriate relations need to be developed for application in different areas. Again, adjusting the rainfall rate and using field derived estimates of T = 65 m^2/d, ρ_s = 1600 kg/m^3, and ϕ = 45° [*Montgomery and Dietrich*, 1994b] in (4) provides a reasonable lower bound to data from sites of observed landsliding (Figure 8).

Comparison of these road drainage surveys with a field survey of channel head locations in this area of Mettman Ridge [*Montgomery and Dietrich*, 1992] reveals that overland flow–initiated channel heads associated with road drainage plot at lower drainage areas than natural channel heads (Figure 9). This presumably reflects the lower infiltration capacity for road surfaces than for natural slopes. Many of the steepest natural channel heads in this area are associated with small landslide scars [*Montgomery and Dietrich*, 1988, 1992]. Contributing areas for road-related landsliding plot within the range of data for natural (i.e., not related to road runoff) channel heads. Drainage area and slope are the main control on landslide occurrence because landsliding depends on subsurface flow. The difference in runoff generation mechanisms between road surfaces and natural slopes does not appear to be as great an influence on the susceptibility to landsliding as does the total drainage area. The small sample size of the available data preclude greater exploration of this issue.

Table 2. Results of Kolmogorov-Smirnov Tests for Mettman Ridge Data

	Channeled Versus Unchanneled	Unchanneled Versus Landslide	Channeled Versus Landside
Area	differ	differ	same
Slope	same	differ	differ

Paired slope and area distributions were tested against the null hypothesis that the distributions are the same at the 0.05 significance level.

Discussion

The lower limit to the data for channel initiation by overland flow and landsliding from road drainage concentration is consistent with the trends described by (2) and (4). The relations reported above apply only to geomorphic impacts on locations immediately downslope of roads; they do not consider a wide array of other road-related impacts that warrant further research. These include more detailed assessments of the integration of road and channel networks, the attendant effects on downstream hydrologic and geomorphic response, and the influence of sediment eroded from road surfaces on substrate sizes in downstream channels. In particular, drainage density increases of the magnitude reported here are likely to have major effects on peak discharges in low-order channels.

Both the uncertainty associated with partitioning road runoff among potential discharge points and the natural variability of soil and road surface properties will contribute

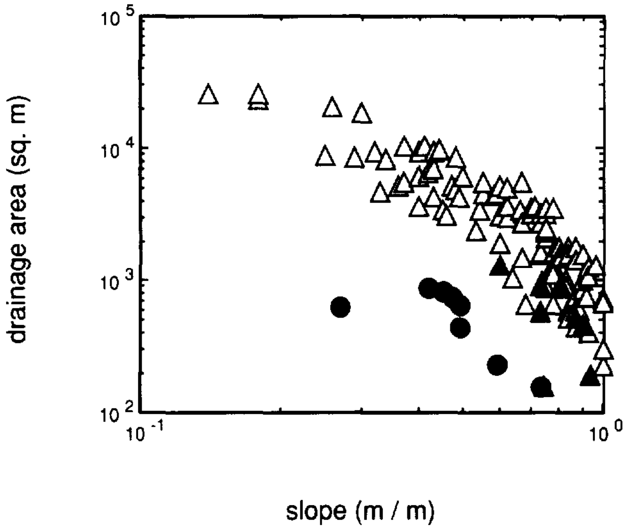

Figure 9. Plot of contributing area versus local slope for channeled data from natural channel heads (open triangles) and road drainage–related landslides (solid triangles) and channel heads (solid circles).

to scatter in data of the type reported here. The Huelsdonk Ridge data, for example, were collected when road runoff was not occurring; drainage area estimates for this study area could have errors as high as ±30% for some data points. The Mettman Ridge data, on the other hand, were collected during and immediately after a small storm; potential errors are likely to be about ±10%. While these errors will not significantly influence the estimated increase in drainage density, they could influence individual data points in Figures 6 and 8. The significant variance expected for data derived from road drainage surveys implies both that empirical thresholds based on such surveys should be fit to as large a data set as possible and that such thresholds provide only a guide to anticipating erosional response to road drainage concentration.

This study has important implications for assessing current road designs. Ridgetop roads presently are recommended as a means to avoid both direct road connection to channels and construction of potentially unstable fill berms across low-order channels [e.g., *Furniss et al.*, 1991]. Ridgetops, however, are generally indented at the heads of even subtle valleys. Thus ridgetop road drainage typically is focused into steep unchanneled valleys, locations prone to shallow landsliding. While recent improvements in road construction practices (e.g., end-hauling) should decrease some road-related impacts, road drainage concentration still may destabilize downslope hillsides or integrate channel and road networks.

The survey results reported here document that incorporating empirical drainage area–slope thresholds into road drainage designs would help to minimize adverse effects of road drainage concentration. This requires determining relations appropriate for the area of interest from field surveys. Fortunately, such surveys are simple and quick. Collecting data from Huelsdonk Ridge, for example, required two people for one day; the Mettman Ridge data required two people for two days. Collecting the necessary data entails a fraction of either the cost of repairing a single landslide or the value associated with resource loss. Such procedures could be readily integrated into road condition surveys conducted during watershed restoration efforts [e.g., *Harr and Nichols*, 1993].

In areas where road surface runoff is of primary concern, the drainage area–slope threshold defines (assuming a road of constant width) a relation between the road length, L, and the gradient of the slope onto which road drainage is discharged. Equations (1), (2), and (4) indicate that the specific relations should reflect the road surface material (infiltration capacity), rainfall characteristics, and soil properties (critical shear stress, friction angle, bulk density, thickness, and conductivity). For the Huelsdonk Ridge data, the empirical relation is approximated by (Figure 10)

$$L = 70\ \mathrm{m}/\sin\theta \qquad (7)$$

and for the Mettman Ridge data by

$$L = 30\ \mathrm{m}/\sin\theta \qquad (8)$$

Adverse erosional impacts associated with ridgetop road construction could be minimized by a drainage system designed to keep the road length contributing to each discharge location less than the criteria defined by relations like (7) and (8). In areas where subsurface flow interception is of primary importance, the total upslope drainage area should be used to define relations like (5) and (6).

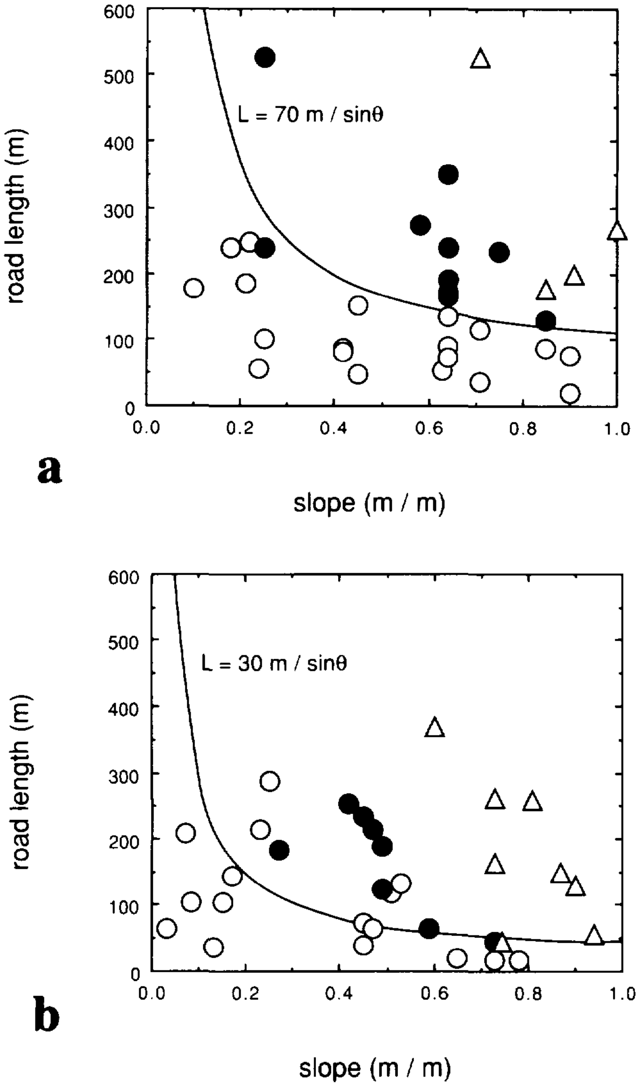

Figure 10. Plot of contributing road length versus ground slope at the point of drainage concentration for (a) Huelsdonk Ridge and (b) Mettman Ridge; data are for unchanneled locations (open circles), channels extending to the drainage outfall (solid circles), and landslides immediately downslope of the drainage outfall (triangles).

The results discussed above highlight the need to include in evaluations of road-related environmental impacts both the frequency along a road that drainage is discharged and the gradient of the slope onto which it is discharged. At present, management regulations generally prescribe culvert spacing based either on delivery of road runoff to natural drainages or a design culvert spacing that varies with the road gradient (e.g., Washington Administrative Code 222-24-025). Road designs or codes that do not take both drainage frequency and ground slope into consideration inadequately address the potential for downslope geomorphic impacts from road drainage concentration.

Conclusions

Road construction fundamentally alters the hydrologic and erosional processes operating in a drainage basin. Concentration of road drainage is associated with both integration of the channel and road networks and landsliding in steep terrain. Many existing road designs, including ridgetop roads, can have significant geomorphic impacts. Simple changes in road design that would reduce drainage concentration, however, could minimize road-related adverse impacts on slope stability and downslope stream channels. Collecting field data to calibrate theoretical thresholds for erosion initiation could be used to generate empirical regional relations for allowable drainage concentration that could reduce road drainage–related impacts.

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