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FOREST ROADS AND GEOMORPHIC PROCESS INTERACTIONS, CASCADE RANGE, OREGON

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ABSTRACT

A major flood in February 1996 triggered more than 100 geomorphic features affecting forest roads in a 181 km^2 study area in the western Cascade Range, Oregon. Eight types of features, including mass movements and fluvial features, were mapped, measured and analysed using geographic information systems and sediment budgets for the road network. Although roads functioned as both production and depositional sites for mass movements and fluvial processes, the net effect of roads was an increase in basin-wide sediment production. Debris slides from mobilized road fills were the dominant process of sediment production from roads. Road-related sedimentation features were concentrated in a portion of the study area that experienced a rain-on-snow event during the storm and was characterized by the oldest roads and steep slopes underlain by unstable, highly weathered bedrock. The downslope increase in frequency of features and volumes of sediment produced, combined with the downslope increase in relative frequency of fluvial over mass-wasting processes, suggests that during an extreme storm event, a road network may have major impacts on stream channels far removed from initiation sites. Overall this study indicated that the nature of geomorphic processes influenced by roads is strongly conditioned by road location and construction practices, basin geology and storm characteristics. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS: forest roads; mass wasting; fluvial erosion; restoration

INTRODUCTION

Forest roads, constructed for timber harvesting, fire management and other objectives, are widespread features of managed forest lands. Forest road networks commonly reach densities equivalent to stream drainage density (FEMAT, 1993; Wemple *et al.*, 1996). Roads in forests are exotic structures that interact with geomorphic, hydrologic and ecological processes with potential effects that range from the local site to broad watershed scales (Forman and Alexander, 1998; Jones *et al.*, 2000).

Roads influence a variety of hydrologic and geomorphic processes. Road surfaces may limit infiltration and increase the rate of fine-grained sediment production in watersheds (e.g. Dunne, 1979; Reid and Dunne, 1984; Fahey and Coker, 1989; Ziegler and Giambelluca, 1997). Debris slides initiated on road cutslopes and fillslopes increase rates of mass wasting relative to forested conditions (Swanson and Dyrness, 1975; Megahan *et al.*, 1978; Coker and Fahey, 1993). In addition, roads may influence sediment production and transport by fluvial processes, where sediment or wood is trapped at stream-crossing culverts and diversion of surface runoff results in culvert failure or gullying of ditches, road surfaces and hillslopes (Weaver *et al.*, 1995; Flannagan, 1999).

The net effect of roads on water and sediment routing varies in time and space, depending upon which processes dominate. High rates of sediment production from road surfaces occur in the years immediately following road construction, but diminish rapidly over time (Fredriksen, 1970; Megahan and Kidd, 1972).

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Road-related sediment production by landsliding often exceeds chronic sediment production from road surfaces (Megahan *et al.*, 1978; Reid *et al.*, 1981), but typically occurs only in response to extreme storms (Swanson and Dyrness, 1975; Coker and Fahey, 1993). In some environments, geomorphic effects of roads may include culvert plugging and gully erosion (Weaver *et al.*, 1995; Flannagan, 1999).

Effects of road networks in whole basins depend on the cumulative effects of many reinforcing and off-setting interactions among road-related processes. Locally, a road segment may interact with mass wasting and fluvial processes in several ways: the road may initiate, transform or intercept a given process and the associated material. At the hillslope scale, the net influence of roads depends upon how processes affected by individual road segments interact as material is transported downslope and into the stream network. At the basin scale, the effect of roads depends upon road network connectivity with the stream network (Wemple *et al.*, 1996; Jones *et al.*, 2000) and the extent to which roads enhance or impede downstream transport of sediment (Nakamura et al., in press).

This study focuses upon the local, hillslope- and basin-scale effects of a forest road network during an individual storm event. An extreme storm event in February 1996 provided the opportunity to examine road network interactions with the routing of water and sediment at a site where some aspects of these interactions had been documented in prior studies (Dyrness, 1967; Fredriksen, 1970; Swanson and Dyrness, 1975; Wemple *et al.*, 1996). We examine effects of the road network on initiation, movement and interception of sediment by a suite of mass-wasting and fluvial processes that operate upon parts or the whole of the road prism–cutslope, ditch, road surface and fillslope (Figure 1).

METHODS

Study area

The study was conducted in the Lookout Creek and Blue River basins, located in the western Cascade Range in Oregon (Figure 2). Bedrock is exclusively of volcanic origin, including highly altered and geomorphically unstable volcaniclastic rocks of late Oligocene to early Miocene origin that occur at elevations below about 1000 m. Relatively stable rocks and soil derived from andesitic and basaltic lava flows of middle to late Miocene age occur at elevations above 1000 m (Swanson and James, 1975).

The Pacific maritime climate of western Oregon is characterized by dry summers and wet winters. Average annual precipitation in the study area ranges from 2300 mm at low elevation to over 2500 mm in higher areas. Over 80 per cent of the precipitation falls between October and May, typically as rain below 400 m (Greenland, 1994). Between 400 and approximately 1200 m, a transient snowpack develops during most winters (Harr, 1981). A seasonal snowpack commonly develops above 1200 m. Forest vegetation is dominated by Douglas Fir (*Pseudotsuga menziesii*) and Western Hemlock (*Tsuga heterophylla*). Timber harvesting and road construction have occurred in the basins since 1950, and by 1990 roughly 25 per cent of the basins were in managed stands, while the road network had reached densities of >2 km km^{-2} (Jones and Grant, 1996) (Table I).

Road age and density vary with elevation and hillslope position in the study basins (Wemple, 1994). Timber harvesting and road construction occurred largely in the 1950s and 1960s in Lookout Creek and from the mid-1960s onward in Blue River. Main-haul access roads, constructed along the valley floor during the 1950s to early 1960s, form the backbone of the road networks in both basins. Connected to these is a network of mid-slope roads, constructed during subsequent decades, that was designed to access distributed harvest units (Silen and Gratkowski, 1953). These valley-floor and mid-slope roads were constructed in areas of the basin underlain by geologically unstable rock types, making them particularly vulnerable to mass wasting. High rates of road-related landsliding documented during the 1964 flood in the region (e.g. Dyrness, 1967; Swanson and Dyrness, 1975) led to modifications in road location and design practices. By the 1970s roads in the basins were constructed on upper slopes, reflecting a regional trend of improved road engineering standards (Sessions *et al.*, 1987).

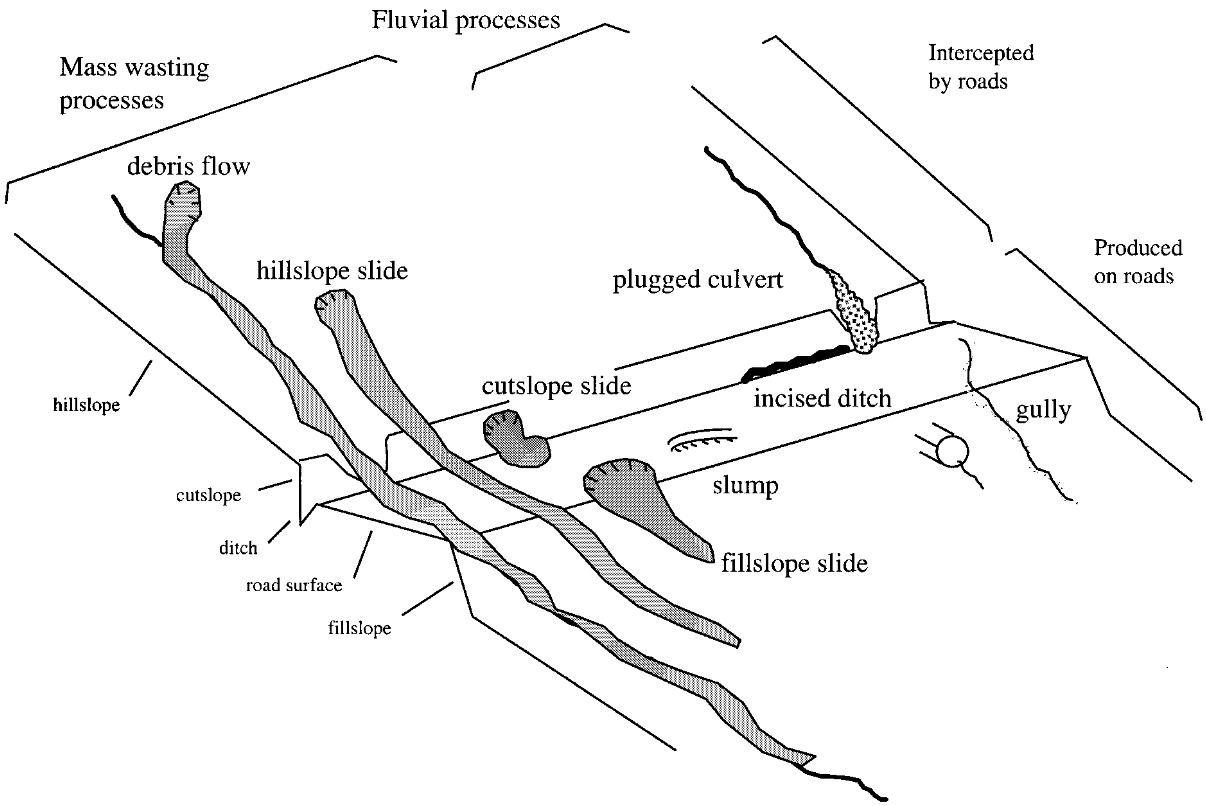

Figure 1. Typology of erosional and depositional features produced by mass-wasting and fluvial processes and associated with forest roads

The February 1996 storm

A sequence of events typical of major floods in western Oregon (Harr, 1981) led up to the February 1996 storm. Following a period of below-average precipitation, prodigious snowfall in late January brought snowpack levels to 112 per cent of the long-term average in the region (Swanson *et al.*, 1998). On the afternoon of 5 February, a strong subtropical jet stream moved into the Pacific Northwest, bringing warm rains from the central Pacific Ocean. Rainfall for the period 5–9 February exceeded 290 mm. Rain and associated snowmelt triggered flood flows with return periods of 30 to 100 years, with profound and diverse geomorphic and ecological impacts (Swanson *et al.*, 1998; Johnson *et al.*, in press).

As is typical of rain-on-snow events in these basins (Perkins, 1997), the relative timing of peak precipitation and snowpack melting differed by elevation during the February 1996 storm. At low elevations (400 to 800 m), rain-saturated snowmelt coincided with peak precipitation intensity, whereas at middle elevations (800–1200 m), maximum snowmelt occurred roughly 24 hours after peak precipitation, and upper elevations (>1200 m) experienced little snowmelt during the event (Dyrness *et al.*, 1996).

Inventory methods and mapped features

In the first few months after the storm, the entire road network in the study area was surveyed by vehicle or on foot. All erosional and depositional features within the road prism (cutslope, ditch, road surface and fillslope) were identified (Figure 1). Locations of features were mapped on 7·5 minute topographic maps and subsequently digitized into a geographic information system (GIS).

Eight types of features were identified, involving erosion and deposition by mass-wasting and fluvial

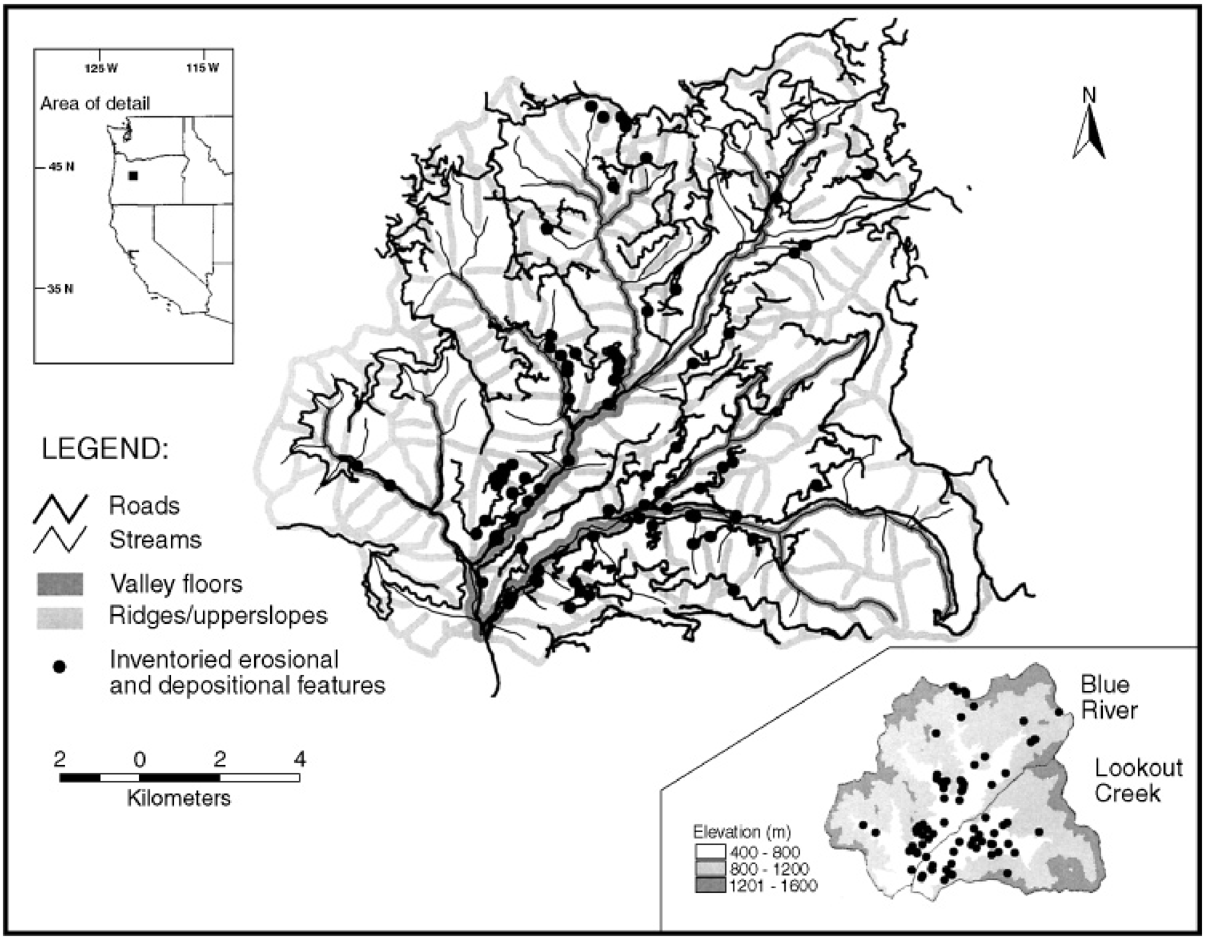

Figure 2. Location map of the Lookout Creek and Blue River basins in the western Oregon Cascades, USA, showing location of roads and stream network, hillslope position classes and erosional and depositional features mapped in this study. Locations of mapped features relative to elevation classes are shown on inset map at lower right

Table I. Summary of characteristics of study basins

	Lookout Creek basin	Blue River basin
Harvested area (%)	22	25
Drainage area (km^2)	62	119
Drainage density ($km\,km^{-2}$)*	3·0	2·9
Road length, total (km)	118	230
Upper slope (km)	27	75
Midslope (km)	73	132
Valley floor (km)	18	23
Road density ($km\,km^{-2}$)	1·9	1·9
Area of basin in roads (%)†	3·1	3·1

* Estimated winter baseflow drainage density (see Wemple *et al.*, 1996)

† Computed using an average width of road cut, surface, and fill of 16 m from Silen and Gratkowski (1953)

processes (Figure 1). Mass movements were defined as discernible erosional scars and depositional features produced by processes involving *en masse* detachment and displacement of sediment and organic debris. Five types of mass movements occurred: some intersected roads but originated above roads (hillslope slides) or occurred in channels (debris flows) but were intercepted by roads, whereas others originated within the road prism (cutslope slides, fillslope slides and slumps). Hillslope slides, cutslope slides and fillslope slides are all debris slides distinguished only by location, while slumps are minor displacements (generally less than 1 m) of blocks of the road prism. Fluvial features were defined as discernible erosional scars and depositional features produced by processes involving particle-by-particle transport of sediment by overland flow or channelized flow. Three types of fluvial features occurred: deposits of bedload that plugged stream-crossing culverts (plugged culverts); ditches incised by diverted streamflow (incised ditches); and road surfaces or hillslopes eroded by diverted streamflow (gullies).

The volume of material detached, transported and deposited was estimated for each feature. Volumes of debris slides, gullies and incised ditches were estimated from measurements of the length, width and depth of the scar features. Debris flow volumes were taken from the volume estimates of contributing debris slides, although the actual volume of a debris flow also included the material entrained and deposited along the channel bed, which was not measured. Sediment volumes associated with plugged culverts were estimated by measuring deposits at culvert inlets, but did not include any material transported through the culvert prior to plugging. The smallest features inventoried were a gully of 5 m^3, a cutslope slide of 10 m^3 and a plugged culvert with 15 m^3 of sediment, but the size of most features ranged from 100 to 6000 m^3 of material removed or deposited.

Sediment budget

Sediment budgets were estimated at each affected site and presented for roads stratified by hillslope position (Figure 3). Volumes of sediment mobilized on hillslopes or in channels above roads (H) and within the road prism (R) were partitioned into the fraction stored on roads (H_s, R_s) and the fraction transported to hillslopes below roads (H_t, R_t), according to:

$$H = H_s + H_t \tag{1}$$

and

$$R = R_s + R_t \tag{2}$$

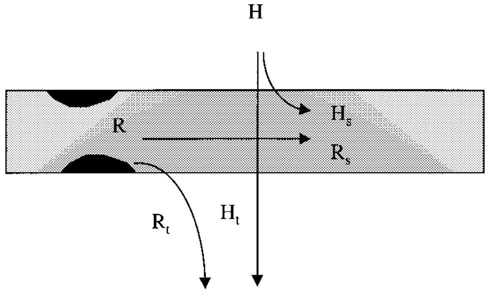

Figure 3. Components of the sediment budget constructed at the scale of individual road segments. Inputs include sediment mobilized from hillslopes or in stream channels above roads (H) and sediment mobilized from within the road prism (R). Sediment contributed to or mobilized on the road could be stored (H_s, R_s) or transported downslope (H_t, R_t)

Net storage of sediment on the road (ΔS) was:

$$\Delta S = H - (H_t + R_t) \tag{3}$$

where H represents material originating on hillslopes and in channels above roads, and $(H_t + R_t)$ represents sediment transported out of the road zone. Substituting Equation 1 into Equation 3 and rearranging, net storage by the road can be expressed as:

$$\Delta S = H_s - R_t \tag{4}$$

Negative values of ΔS indicate that roads were a net source, or production site, for sediment. Here, sediment source refers to material mobilized on slopes or in channels and moved downslope many metres (except in the case of slumps) where it was either delivered to channels or held in storage for possible delivery to channels during subsequent events. Positive values of ΔS indicate that roads functioned as a net storage site for sediment derived from upslope, preventing the delivery of sediment to channels or terminating the transport of sediment within channels. Much of this stored sediment was placed below roads or removed from the site during maintenance activities following the storm.

Spatial distribution

The elevation, road age and slope position of each feature were identified by overlay analyses in a GIS. Three elevation zones within the study area were identified from a digital elevation model of the basin. Elevation zones were chosen to correspond with observed rainfall–snowmelt dynamics described above: low elevations (400 to 800 m), middle elevations (800 to 1200 m) and high elevations (>1200 m). Road age was identified from historical aerial photographs (Jones and Grant, 1996; Wemple *et al.*, 1996). Road age classes corresponded to periods of different road construction rates and designs: prior to 1960, 1960–1969, 1970–1979, 1980–1995.

The basin was partitioned into upper slope, mid-slope and valley floor zones using GIS layers of the stream network and the digital elevation model of the basin (Figure 2). Hillslope positions were chosen to represent distinct combinations of gradient and the potential for upslope contribution of water and sediment to roads. On upper hillslopes (defined as the area within 100 m on either side of major ridges), gradients are generally steep, and concentration of surface runoff by roads may lead to slope instability (Montgomery, 1994). Roads located on upper slope positions have few intersections with streams and little potential for interception of groundwater or sediment, due to limited extent of upslope areas (Wemple, 1998). On mid-slopes (defined as areas outside of upper slopes and valley floors), gradients are steep, there are many road–stream crossings (Jones *et al.*, 2000) and there is a high potential for interception of groundwater and sediment by roads (Wemple, 1998). On valley floors (defined as areas within a 200 m distance on either side of fifth-order channels, or within a 100 m distance on either side of fourth-order channels, including floodplains, terraces and alluvial fans), gradients are low, but roads cross higher-order tributary streams (Jones *et al.*, 2000). Here, there is a high potential for interception of streamflow and sediment by roads, especially those immediately adjacent to steep hillslopes.

Process interactions

Cascading sequences of geomorphic processes, or ‘disturbance cascades’ (Nakamura *et al.*, in press), were examined for the set of inventoried features. Features that appeared to have triggered other features downslope or elsewhere along the road were identified by tracing each feature from its initiation site along the runout pathway.

Table II. Numbers and frequencies (numbers per kilometre of road length) of inventoried features in the Lookout Creek and Blue River basins

	Lookout Creek basin		Blue River basin		Total	
	No.	No./km	No.	No./km	No.	No./km
Mass movements						
Debris flows	9	0·08	7	0·03	16	0·05
Hillslope slides	4	0·03	1	0·004	5	0·01
Cutslope slides	1	0·01	11	0·05	12	0·03
Fillslope slides	18	0·15	13	0·06	31	0·09
Slumps	1	0·01	12	0·05	13	0·04
Total	33	0·28	44	0·19	77	0·22
Fluvial features						
Plugged culverts	3	0·03	10	0·04	13	0·04
Incised ditches	1	0·01	2	0·01	3	0·01
Gullies	5	0·04	5	0·02	10	0·03
Total	9	0·08	17	0·07	26	0·07
Grand total	42	0·36	61	0·27	103	0·30

RESULTS

Numbers, frequencies, volumes and interactions among features

A diverse suite of geomorphic processes occurred during the February 1996 flood event, producing 103 mapped features associated with roads in the Lookout Creek and Blue River basins (Table II). The vast majority of these features occurred in the southern portion of the study area at low elevation sites (Figure 2). Mass movements were more numerous than fluvial features, and sediment production exceeded sediment storage by roads. Three-quarters of the inventoried features were mass movements, and one-quarter were fluvial features. Two-thirds of the features involved sediment production from roads, in the form of cutslope slides, fillslope slides, incised ditches and gullies, while one-third involved sediment capture, in which roads intercepted debris flows, hillslope slides and bedload (Table II).

Fillslope slides were the most numerous and frequent type of feature. They accounted for 30 per cent of all mapped features and 40 per cent of mass movements, with approximately one occurrence for every 10 km of road length in the two basins (Table II). Together, cutslope slides and slumps accounted for one-quarter of all inventoried features and one-third of mass movements, with average frequencies of three (cutslope slides) or four (slumps) for every 100 km of road. Hillslope slides and debris flows that were intercepted by roads accounted for the remaining mass movements inventoried.

Stream-crossing culverts plugged by bedload accounted for half of the fluvial features that were inventoried, while gullying of road surfaces and fillslopes also was relatively common. Plugged culverts and gullies together accounted for almost one-quarter of the features inventoried and nearly all (90 per cent) of the fluvial features, with average frequencies of three (gullies) or four (plugged culverts) for every 100 km of road.

Roads intercepted, stored and produced sediment, but overall were a net source of sediment to hillslopes and channels in the two basins (Table III). Roads intercepted almost 26 000 m^3 of sediment contributed from hillslopes and channels and stored over 19 000 m^3 of sediment. However, more than 32 000 m^3 of sediment were mobilized within the road prism, so roads were a net source of more than 13 000 m^3 of sediment in these two basins during this event. Debris flows accounted for two-thirds of the sediment intercepted by roads, and hillslope slides and bedload trapped at stream-crossing culverts accounted for the remaining one-third. Fillslope slides accounted for four-fifths of sediment mobilized within road prisms, while cutslope slides accounted for most of the remaining one-fifth; ditch incision and gullying accounted for less than 5 per cent of the total sediment volume eroded from roads. Most of the sediment stored on roads was from debris flows, but

Table III. Sediment budget for road-associated features inventoried after the February 1996 storm in the Lookout Creek and Blue River basins. Sediment volumes (m^3) are shown as basin totals and by hillslope position (see text). Net storage (ΔS) = $H - (H_t + R_t)$

	Debris flows	Hillslope slides	Cutslope slides	Fillslope slides	Plugged culverts	Incised ditches	Gullies	Total	Net storage (ΔS)
Upper slope roads									
From hillslopes, streams (H)	0	0	0	0	0	0	0	0	
From road prism (R)	0	0	0	5450	0	0	0	5450	
Stored on roads ($H_s + R_s$)	0	0	0	0	0	0	0	0	
Exported ($H_t + R_t$)	0	0	0	5450	0	0	0	5450	−5450
Mid-slope roads									
From hillslopes, streams (H)	4700	6985	0	0	790	0	0	12 475	
From road prism (R)	530	5	4255	19 110	0	480	185	24 565	
Stored on roads ($H_s + R_s$)	3120	1880	4120	0	790	0	0	9910	
Exported ($H_t + R_t$)	2110	5110	135	19 110	0	480	185	27 130	−14 655
Valley-floor roads									
From hillslopes, streams (H)	12 410	575	0	0	175	0	0	13 160	
From road prism (R)	565	0	145	1095	0	160	305	2270	
Stored on roads ($H_s + R_s$)	8450	535	135	0	175	0	0	9295	
Exported ($H_t + R_t$)	4525	40	10	1095	0	160	305	6135	+7025
All roads (basin total)									
From hillslopes, streams (H)	17 110	7560	0	0	965	0	0	25 635	
From road prism (R)	1095	5	4400	25 655	0	640	490	32 285	
Stored on roads ($H_s + R_s$)	11 570	2415	4255	0	965	0	0	19 205	
Exported ($H_t + R_t$)	6635	5150	145	25 655	0	640	490	38 715	−13 080

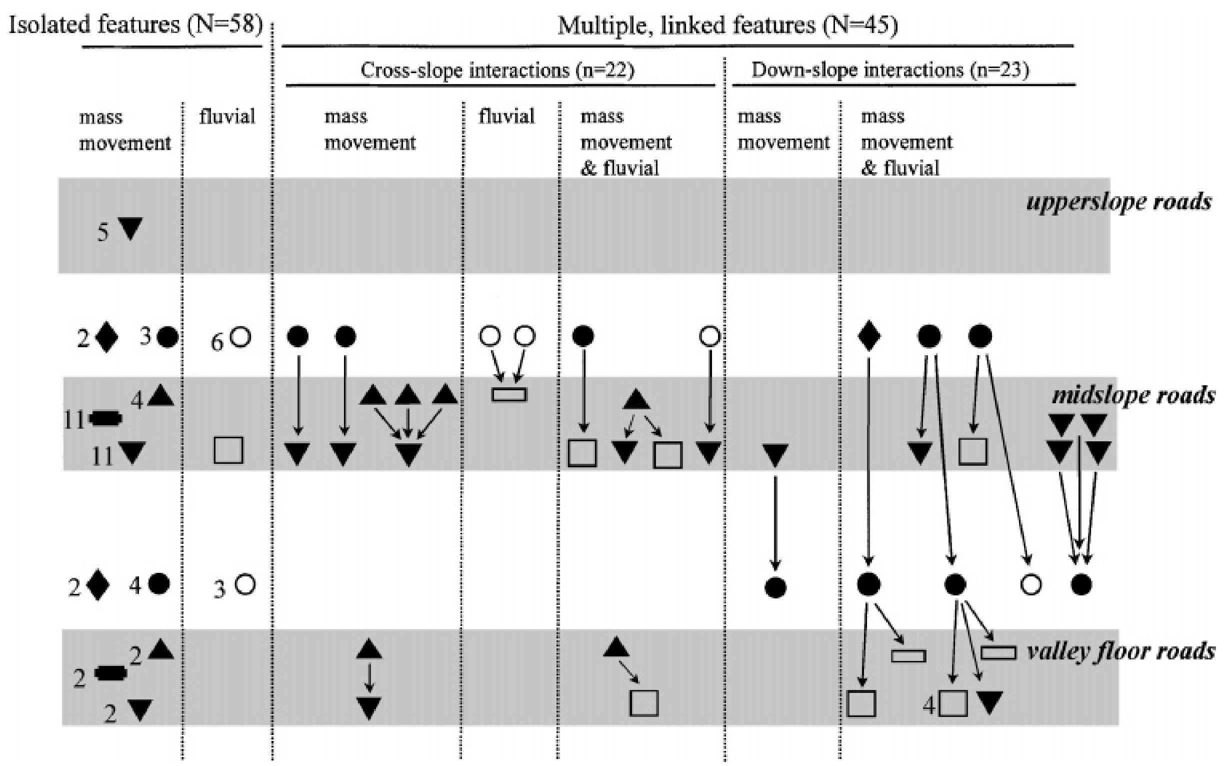

Figure 4. Schematic representation of the distribution and spatial complexity of features inventoried in this study. Closed symbols represent mass movements (●, debris flows; ◆, hillslope slides; ▲, cutslope slides; ▼, fillslope slides; ▬, slumps). Open symbols represent fluvial features (○, plugged culverts; ▭, incised ditches; □, gullies). Features are positioned relative to point of origin, on hillslopes above roads or within the road zone (represented by grey bars). Arrows indicate features that triggered an associated feature, and show impacts to multiple tiers of roads where applicable. Numbers beside symbols indicate number of inventoried features of that type

cutslope slides, hillslope slides and bedload (i.e. in plugged culverts) contributed small fractions of the sediment stored on roads. Fillslope slides accounted for two-thirds of the net sediment exported from roads, but debris flows and hillslope slides accounted for most of the remaining one-third (Table III).

Slightly more than half (56 per cent) of the erosional and depositional features associated with roads occurred as solitary events, unconnected with other inventoried features (Figure 4). All of the inventoried slumps occurred as solitary events, apparently unaffected by diverted surface runoff or other documented mechanisms. Most (nine of 13) plugged culverts occurred as solitary events, and apparently did not lead to gullying or fill failure. Most (four of five) hillslope slides deposited sediment on roads without triggering additional erosion within the road prism.

Two types of complex, interacting sets of inventoried features were observed on roads, involving almost half (44 per cent) of all mapped features: (1) hillslope slides, cutslope slides or bedload in ditches or culverts led to diversions of surface runoff and triggered fillslope slides, gullying or ditch incision; and (2) fillslope slides entered stream channels and became debris flows (Figure 4). One-quarter of the 22 fillslope slides on mid-slope roads were apparently connected to debris flows intercepted by roads (three cases), cutslope slides in the road prism (two cases) or plugged culverts (one case). Seven of ten instances of gullying were connected to debris flows, and two were connected to cutslope slides in the road prism. Ditch incision was also connected to debris flows (two of three cases) or plugged culverts (one case). One-quarter of the fillslope slides on midslope roads entered channels and became debris flows (five cases).

Table IV. Distribution and frequency (numbers per kilometre of road length) of mass-movement and fluvial features associated with roads, according to hillslope position and function of the road in intercepting or producing sediment

	Number		Frequency (no./km)	
Slope position function	Mass movement	Fluvial feature	Mass movement	Fluvial feature
Upper slope roads				
Intercepted by roads	0	0	0	0
Produced on roads	5	0	0·05	0
Total	5	0	0·05	0
Mid-slope roads				
Intercepted by roads	11	9	0·05	0·04
Produced on roads	41	5	0·20	0·02
Total	52	14	0·25	0·06
Valley-floor roads				
Intercepted by roads	10	4	0·24	0·10
Produced on roads	10	8	0·24	0·20
Total	20	12	0·48	0·30

Hillslope-scale effects

Numbers and frequencies of erosional and depositional features associated with roads, and volumes of sediment transported, varied with hillslope position (Table IV). The frequency of features per unit road length increased markedly in the downslope direction. Inventoried features were six times more frequent on mid-slope roads compared to upper slope roads, and 2·5 times more frequent on valley-floor roads compared to mid-slope roads.

Mass movements decreased in frequency relative to fluvial features in the downslope direction (Table IV). Mass movements were the only type of features observed on upper slopes. Fluvial features accounted for 21 per cent of inventoried features on mid-slopes and 38 per cent of inventoried features on valley floors.

Features producing sediment from the road prism also decreased in frequency in the downslope direction relative to features intercepting sediment on road surfaces (Table IV). Upper slope roads functioned only to produce sediment. On mid-slopes, features that produced sediment on roads were 2·3 times more frequent than features that originated outside the road prism, while on valley-floor roads the number of features initiated on roads was almost equal to the number of features intercepted by roads.

The volume of sediment produced from roads (R) was higher in mid-slope positions than upper slope or valley-floor positions, but sediment volumes produced on roads decreased in the downslope direction relative to sediment volumes contributed to roads from slopes and streams (H) and sediment stored on roads ($H_s + R_s$) (Table III, Figure 4). Upper slope roads were exclusively sources of sediment (Table III), although little of this material moved beyond the road prism in this event (Figure 4). Mid-slope roads were major sources of road-related sediment, accounting for three-quarters of the total road prism sediment production and producing sediment at a rate of 120 $m^3\,km^{-1}$ of road (Table III). Roads in mid-slope positions were net sources of sediment, producing twice the volume of sediment that was intercepted from upslope and upstream sources (Table III). Much of the sediment stored on roads originated on hillslopes unaffected by upper slope roads, whereas much of the sediment produced from mid-slope roads moved downslope, reaching valley floor roads (Figure 4). On valley floors, sediment production from the road prism (55 $m^3\,km^{-1}$ of road) was very similar to that on upper slopes (53 $m^3\,km^{-1}$ of road length) (Table III). Valley-floor roads were net storage sites for sediment, intercepting and storing roughly four times more sediment than was eroded from these roads. Valley-floor roads stored 227 $m^3\,km^{-1}$ of sediment compared to 48 $m^3\,km^{-1}$ on midslope roads (Table III).

The frequency of solitary features decreased in the downslope direction relative to the frequency of complexes of associated features (Figure 4). On upper slopes, none of the five fillslope failures was connected

Table V. Road lengths (km) and numbers of inventoried features in the Lookout Creek and Blue River basins broken down by decade of road construction and elevation classes.

	Lookout Creek Basin					Blue River Basin				
	<1960	1960–69	1970–79	1980–95	Total	<1960	1960–69	1970–79	1980–95	Total
(a) Road length (km)										
Elevation										
400–800 m	44·7	12·8	0·3	0·3	58·1	26·6	21·0	11·8	1·2	60·6
801–1200 m	24·0	9·9	1·8	0·4	36·1	4·1	37·0	54·0	20·9	116·0
>1200 m	3·2	19·3	0	1·5	24·0	10·5	17·7	20·4	5·1	53·7
Total	71·9	42·0	2·1	2·2	118·2	41·2	75·7	86·2	27·2	230·3
(b) No. of features										
Elevation										
400–800 m	31	6	1	0	38	20	7	6	3	36
801–1200 m	3	0	0	0	3	6	6	10	3	25
>1200 m	1	0	0	0	1	0	0	0	0	0
Total	35	6	1	0	42	26	13	16	6	61

to another inventoried feature. On midslopes, 42 per cent (28 of 66) of inventoried features were associated with one or more features. Five of the complex features on mid-slope roads began as debris flows from above the road. Also, five debris flows produced from mid-slope roads affected valley floor roads (Figure 4). On valley floors, 53 per cent (17 of 32) of inventoried features were connected to one or more features.

Basin-scale effects

The two study basins had quite similar frequencies of road-related erosion and sedimentation (Table II). Mass movements represented roughly three-quarters of the features in both basins, and the relative proportions of individual feature types were rather similar between basins. In Blue River, where more roads were constructed in upper slope positions and in recent decades, cutslope slides and slumps were more frequent than in Lookout Creek basin, where roads were constructed in lower hillslope positions and earlier.

The highest frequency of road-related features in both basins occurred on roads that had been constructed prior to 1960 at elevations below 800 m (Tables II and V). In the Lookout Creek basin, over 80 per cent (35 of 42) of the features occurred on 61 per cent of the road length that had been constructed prior to 1960, while over 90 per cent (38 of 42) of the features occurred on 50 per cent of the road length that occurred below 800 m. Thus, in Lookout Creek, road-related features were 1·4 times more frequent on roads constructed prior to 1960 than for the basin as a whole (0·49 vs. 0·36 features/km), 1·8 times more frequent on roads constructed below 800 m than for the basin as a whole (0·65 vs. 0·36 features/km), and 1·9 times more frequent on roads constructed prior to 1960 and below 800 m than for the basin as a whole (0·70 vs. 0·36 features/km).

In the Blue River basin, 43 per cent (26 of 61) of the features occurred on 18 per cent of the road length that had been constructed prior to 1960, while 60 per cent (36 of 61) of the features occurred on 27 per cent of the road length that occurred below 800 m. Thus, in Blue River, road-related features were 2·3 times more frequent on roads constructed prior to 1960, or below 800 m, than for the basin as a whole (0·65 vs. 0·27 features/km, 0·60 vs. 0·27 features/km), and 2·8 times more frequent on roads constructed prior to 1960 and below 800 m than for the basin as a whole (0·75 vs. 0·27 features/km).

DISCUSSION

The road network interacted with geomorphic processes in the landscape during this storm event, producing a complex pattern of road-related erosion and deposition. Although roads functioned as both initiation and depositional sites for mass movements and fluvial processes, the net effect of roads was an increase in basin-wide sediment production. Road-related sedimentation features were concentrated in a portion of the study area that experienced a classic rain-on-snow event during the storm and was characterized by the oldest roads and slopes underlain by unstable, highly weathered bedrock. The downslope increase in frequency of features and volumes of sediment produced, combined with the downslope increase in relative frequency of fluvial over mass-movement processes, suggests that during an extreme storm event, a road network may have impacts on hillslopes and stream channels far removed from initiation sites. Overall this study indicated that the nature of geomorphic processes influenced by roads is strongly conditioned on road location and construction practices, basin geology and storm characteristics.

Fillslope slides were the dominant process of sediment production from roads. Fillslope slides initiated on steep hillslopes often transported sediment significant distances from initiation sites. More than half (over 13 000 m^3) of the sediment produced by fillslope slides was delivered to channels in the study basins (F.J. Swanson, unpublished data).

Sediment interception and storage by roads was an important aspect of this study, but only certain combinations of road position and geomorphic processes led to sediment interception. Cutslope slides on mid-slope roads resulted in nearly complete storage of sediment, because of the near-horizontal configuration of the road surface below the initiation site. Sediment storage for debris flows and hillslope slides was less effective, particularly on mid-slope roads, presumably due to higher energy and lower viscosity conditions for material mobilized by these processes. Sediment storage was most effective on valley-floor roads, in part because of the generally low gradient of adjacent landforms, such as alluvial fans and terraces.

This study corroborates the finding of other studies (e.g. Reid *et al.*, 1981) that road-related erosion processes increase overall sediment production in forested basins. Road-related debris slides inventoried in this study represented almost half (44 per cent) of the 80 debris slides (>75 m^3) inventoried after the February 1996 storm (F.J. Swanson, unpublished data), while road-related debris slides represented 60 per cent of the total inventoried after the December 1964 and January 1965 storms (Dyrness, 1967). In steep forested landscapes of western Oregon, debris slides (distinguished as hillslope, fillslope and cutslope slides in this study) have been a dominant source of sediment both along roads (this study) and in the larger landscape (Swanson and Fredricksen, 1982).

A number of geographically overlapping factors apparently contributed to the concentration of features in the southern, low-elevation portion of the study area. This low-elevation area had distinct geology, road ages and snowmelt patterns during the storm event. The oldest roads in the Lookout Creek and Blue River basins were constructed at low elevations, where highly weathered volcanic rocks contribute to inherent slope instability (Dyrness, 1967; Swanson and Dyrness, 1975). This low-elevation zone, particularly between 400 and 800 m, experienced snowmelt coincident with maximum precipitation during the February 1996 storm, whereas snowmelt was delayed at higher elevations (Dyrness *et al.*, 1996). The coincidence of older roads on unstable soils at elevations exposed to rapid snowmelt prevents the clear discrimination of a single explanatory factor responsible for the concentration of features in this portion of the study area.

Roads appear to contribute to sequences of linked geomorphic processes that may affect hillslopes and stream channels far downstream of initiation sites. During a single storm event, geomorphic processes often occur as cascading sequences of linked features, such as debris slides on hillslopes transforming into debris flows in small tributary stream channels and ultimately wood and sediment pulses in large mainstem channels (Nakamura *et al.*, in press). In some cases in this study, roads increased the frequency of debris slides, supplemented the volume of debris flows, and partitioned debris flows into sediment intercepted on the road surface and water that flowed down the road and entered an adjoining stream channel. Long portions of the stream network in Lookout Creek and Blue River were scoured by debris flows that originated as fillslope slides from mid-slope roads (K. Snyder, Oregon State University, unpublished). Considerable streambank erosion occurred along debris flow paths and in some areas downstream of those paths or of drainage diversions.

The relationship between geomorphic processes and road location has numerous implications. Our findings suggest that older roads in mid-slope positions continue to dominate the production of sediment during extreme storms, despite improvements in the construction and location of roads in recent decades. Engineering efforts directed at maintaining or restoring mid-slope roads on unstable hillslopes may be particularly effective in minimizing future impacts. In addition, efforts might be directed toward reducing the role of roads in downslope cascades of mass-movement and fluvial processes such as those documented in this study. In our study area, the high frequency of road-related features along valley-floor roads prevented access to the basins temporarily, and some areas were inaccessible for many months, indicating that engineering measures to protect main-access valley-floor roads or provide for more effective passage of sediment may be relatively cost effective. Our spatially explicit inventory of road-related sedimentation features illustrated particular connections between the road network and geomorphic processes in a steep forested landscape of western Oregon; replication of this approach in other landscapes could contribute valuable insights for road engineering and geomorphology.

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