Reprinted from the *Journal of Environmental Quality*
Vol. 20, no. 1, January–March 1991,
677 South Segoe Road, Madison, WI 53711 USA

(1203)

Downstream Effects of Timber Harvesting on Channel Morphology in Elk River Basin, Oregon

Sandra E. Ryan and Gordon E. Grant

Downstream Effects of Timber Harvesting on Channel Morphology in Elk River Basin, Oregon

Sandra E. Ryan* and Gordon E. Grant

ABSTRACT

Downstream effects, a type of cumulative watershed effect, were identified using changes in the width and distribution of open riparian canopies measured from aerial photography taken between 1956 and 1979 in Elk River basin, southwest Oregon. Open canopies appear on aerial photographs of densely forested basins as unvegetated areas bordering stream channels. Opening occurs when large disturbances, such as landslides, debris flows, large floods, and excessive sedimentation, disrupt the vegetation in the riparian corridor. Downstream changes in channel morphology, inferred by the changing pattern of open reaches were linked to upslope forestry activities; a causal link was assumed where: (i) open reaches extended continuously downstream from clearcuts and roads or (ii) the timing and pattern of opening downstream varied in direct relation to the intensity of upslope forestry activities. Open riparian canopies were observed in first- through fifth-order channels, though only 11% of open reaches in low-order channels were spatially connected to open reaches in higher order channels. Open reaches on low-order tributaries were attributed to landslides and surface erosion generated from clearcuts and roads; the total length of open reaches in low-order channels increased 30-fold during the study period. Open reaches occurred on higher-order channels throughout the study period but did not increase in size or change location in relation to upslope harvest activities. Instead, open canopies were restricted mainly to wide and low gradient channel reaches, which comprised approximately one-third of the length of higher-order channels. Limited downstream change in riparian canopies associated with upslope forestry activity during the study period, which included a 100-yr storm, was attributed to three physical factors: (i) lack of debris flows in most parts of the basin; (ii) channels constrained by competent hillslopes limiting the potential for opening; and (iii) low harvest levels over much of the basin at the time of the 100-yr storm. While air photo interpretation proved useful in deciphering the gross disturbance history of the basin and in distinguishing the general processes which generate downstream effects, sedimentation processes that do not disturb the riparian canopy may also be active in Elk River basin but were not detected due to the coarseness of the techniques used.

S.E. Ryan, INSTAAR and Dep. of Geography, Campus Box 450, Univ. of Colorado, Boulder, CO 80309-0260; and G.E. Grant, U.S. Forest Service, Pacific Northwest Res. Stn., 3200 Jefferson Way, Corvallis, OR 97331. Received 23 Apr. 1990. *Corresponding author.

Published in J. Environ. Qual. 20:60–72 (1991).

DOWNSTREAM EFFECTS, a type of cumulative watershed effect, are persistent impacts, separated in time and space from the original landscape disturbance. Downstream effects of forest practices can occur when forestry activities induce changes in the ways water, sediment, and woody debris move through the basin and are delivered to higher-order channels. Logging and road construction can produce changes in on-site conditions, including altering hillslope cover and contour, compacting soils, and reducing root strength. These on-site changes can alter on-site processes by reducing infiltration rates, expanding drainage networks, and increasing inputs of sediment and woody debris into river channels. Changes in on-site conditions and processes can, in turn, increase the amount, frequency, and rate of water, sediment, and debris movement through the drainage network. As a result, channels downstream can experience changes in width, depth, or stability, producing damage to structures and riparian zones and affecting aquatic habitat in areas far removed from the original forestry activity.

The purpose of this study was to determine if downstream effects from forestry activities could be detected in Elk River basin using air photo interpretation and to identify the specific processes that generated these effects. Distinguishing between channel changes produced primarily by peak flows as opposed to increased sediment transport, for example, is important to help resource managers design effective mitigation measures. A sequential analysis was conducted to quantify the timing, magnitude, and persistence of channel changes over a 23-yr period. Air photo interpretation based on the RAPID (Riparian Air Photo Inventory of Disturbance) technique (Grant, 1988) was used to link upslope disturbances with changes in fourth- and fifth-order tributaries. Both logged and unlogged basins were analyzed to separate the changes produced by timber harvesting from those that occurred under natural conditions.

Changes in channel morphology in the Pacific Northwest are difficult to identify from air photos due to dense forest cover over the channels. Changes in conditions in fourth- and fifth-order channels in Elk River basin could be identified and measured on aerial photographs, with scales ranging from 1:12 000 to 1:24 000, by openings in the riparian canopy cover. Open reaches appear on air photos as unvegetated areas or gaps in the riparian canopy cover or white streaks bordering the channel in areas where the riparian vegetation has been harvested (Fig. 1). Open reaches can be distinguished by tonal variation on air photos since they are distinctively lighter than surrounding clearcuts, forest, or vegetated channel surfaces. Because this is an indirect measure of channel condition, some background on the processes that create open riparian canopies is necessary (see the next section).

In addition to measuring open reaches on air photos, sediment impacts on the main stem Elk River (sixth-order) were assessed by correlating the change in number and location of gravel bars between photo intervals with the volume of landslides generated in tributary basins as estimated from air photos and checked with field measurements by McHugh (1986). Sediment delivered to rivers accumulates in characteristic locations where flow patterns produce similar erosional and depositional sequences from one high flow even to another (Lisle, 1986). As a result, the location of gravel bars tends to be fixed and their size is relatively constant unless significant changes in sediment supply or flow occur. Hence, the distribution of gravel bars reflects the current channel regime and an increase in the number of gravel bars can be used as corroborative evidence of increased sediment deposition due to changes in upstream land uses.

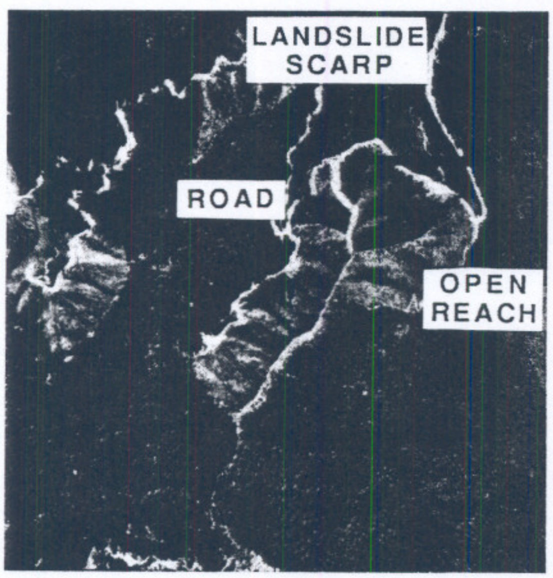


Fig. 1. Example of open reach on air photo of Bald Mountain Creek, 1969. Scale of photo is approximately 1:31 680, reduced from 1:15 840.

CAUSES AND APPEARANCES OF RIPARIAN CANOPY OPENING

Open canopies are produced by disturbances which uproot or increase the mortality of riparian vegetation, such as landslides, debris flows, severe floods, and excessive sedimentation. Such disturbances destroy mature or young forest stands adjacent to stream channels. Though opening of the riparian canopy cover reflects disturbance or removal of vegetation by physical processes, it is evidence of a change in the movement and distribution of material in the drainage network, since the processes that create open reaches are driven by the movement of water, sediment, and debris. Subsequent channel stabilization and recovery is indicated by a decrease in the open area as channel surfaces are revegetated.

Patterns of open canopies were used to infer the response of channels to forestry activities in all parts of Elk River basin, though the specific processes that create open reaches vary by stream size and location (Fig. 2). Open reaches in low-order channels (first- through third-) result primarily from landslides and associated debris flows (McHugh, 1986); the latter commonly occur during large storms when saturated hillslope material enters a channel charged with water. The abrupt input of sediment, debris, and boulders, along with the shear stresses generated by the debris flow moving down-channel uproots trees, producing a gap in the riparian canopy cover. The moving mass

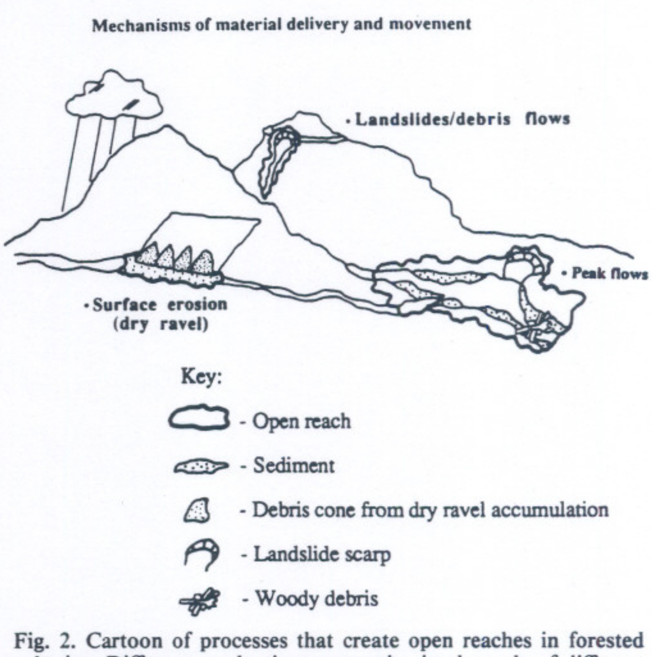


Fig. 2. Cartoon of processes that create open reaches in forested basins. Different mechanisms are active in channels of different stream order. Debris flows commonly occur in low-order channels while impacts from peak flows prevail in higher-order channels. Channel changes attributed to surface erosion occur mainly where harvested units intersect the stream channel.

erodes unstable banks, toeslopes, and channel beds, adding additional material to the flow and extending the track of scouring, battering, and canopy removal further downstream. The entire mass may eventually enter higher-order channels, where the debris flow may stop or undergo a further change in rheology due to the addition of water. In the latter case, the debris flow is transformed into a debris-laden flood and the path of destruction may continue for several kilometers downstream (Costa and Jarrett, 1981; Costa, 1984). The result is a continuous opening in the riparian canopy cover which appears on air photographs as a white path extending downstream from a landslide headscarp, surrounded by darker-toned forest or clearcuts. The path of continuous opening produced by the debris flow can be used to spatially link downstream channel changes to upslope disturbances produced by forestry activities.

Open reaches on higher-order channels (fourth- and fifth-) can occur by fluvial processes alone. Vegetation on floodplains, terraces, alluvial fans, and gravel bars can be battered and uprooted by peak flows and transport of wood and sediment over these surfaces, removing the riparian canopy cover. Bank failures and undercutting of terraces will also produce open reaches. Open reaches in higher-order channels appear on photos as unvegetated channel surfaces; the width of the open reach includes the active channel and mid-channel gravel bars. Channel surfaces colonized by small trees and shrubs appear darker than the active channel and are excluded from the measurement of open reaches.

Finally, open reaches in both high- and low-order channels can be produced by surface erosion, specifically dry ravel and small, shallow failures from harvested slopes. Dry ravel refers to the continual downslope movement of soil and angular, coarse rock fragments by gravity. In the study area, it occurs in droughty, coarse-textured, noncohesive soils where revegetation of harvested slopes is poor (McHugh, 1986). Ravelling slopes are not confined to channels or swales but often encompass entire hillslopes. They are identified on air photos by smooth, light-toned hillslopes devoid of vegetation or by several small, light colored streaks running parallel to the direction of the hillslope. Although some surface erosion occurs in conjunction with landslides, dry ravel is distinguished from landslides on air photos by the absence of arcuate headscarps. Surface erosion by dry ravel can be a locally significant and voluminous source of material that produces an open reach by burying or killing riparian vegetation.

STUDY SITE

Elk River drains a 200-km^2 basin in the Klamath Mountain Province of southwest Oregon (Fig. 3); 90% of the study site is under the administration of the Siskiyou National Forest, whereas the remaining area is privately owned. The bedrock consists of metamorphic and igneous rocks of Jurassic age and sedimentary rocks of Cretaceous age. Mass movements occur throughout the basin, though each lithology has inherently different failure types and rates (McHugh, 1986). Although landslides are common in all lithologies, debris flows are limited to areas underlain by quartz-diorite. Surface erosion—specifically, dry ravel and shallow soil slips—is generated from clearcuts in Cretaceous sedimentary terranes. Deep-seated earthflows occur in areas of Jurassic metamorphic rock. Large landslides often occur along streams at contacts between two lithologies of different competence.

Like most south coastal Oregon streams, Elk River has relatively high sediment transport rates. The annual suspended sediment yield, estimated from suspended sediment measurements, is approximately 350 Mg/km^2 per year—two to three times the yields of northern and middle coastal Oregon streams (Karlin, 1980). High sediment discharges are attributed to steep river and hillslope gradients, highly fractured and altered rocks, and high rainfall intensities common to the Klamath Mountain Province.

The climate of the basin is strongly influenced by air masses moving inland off the Pacific Ocean. A wet season between October and April provides 95% of the yearly precipitation (National Climate Center, 1983). Winter storms tend to be long and of low intensity; temperatures are mild and snow cover is rare except at the highest elevations. Stream flow patterns typically follow the seasonal distribution of precipitation and peak flows occur when infrequent heavy rains are preceded by a prolonged wet period. Saturated antecedent conditions increase the potential for mass movements, and landslides frequently occur during large storms (Varnes, 1978). Records of peak flows from the South Fork Coquille River at Powers were used to index the flood history as flow records from the Elk River gauge are incomplete. Significant peak flows (greater than 10-yr return interval) were recorded in 1944, 1955, 1964, 1971, and 1974. The largest storm occurred in the winter of 1964–1965 (USGS Water Resources Data for Oregon, Portland) and had an 80

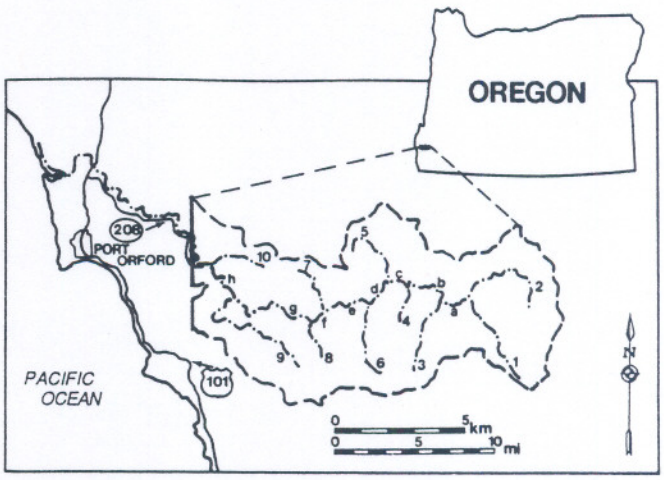


Fig. 3. Map of Elk River basin. Channel names are as follows: (*1*) South Fork Elk River, (*2*) North Fork Elk River, (*3*) Blackberry Creek, (*4*) Milbury Creek, (*5*) Butler Creek, (*6*) Panther Creek, (*7*) Red Cedar Creek, (*8*) Purple Mountain Creek, (*9*) Bald Mountain Creek, and (*10*) Anvil Creek. Lower-case letters on main stem Elk River refer to channel segments inventoried by gravel bar count. Study was limited to drainage basin area west of Siskiyou National Forest Boundary (solid line). Dashed line indicates watershed boundary; dot and dash lines depict drainage network.

to 150-yr return interval. This storm is referred to throughout this paper as the 1964 storm.

Elk River has valuable fisheries and timber resources. The main stem and its tributaries provide excellent habitat for chinook salmon (*Oncorhynchus tschawytscha*), steelhead trout (*Salmo gairdneri*), cutthroat trout (*Salmo clarki*), and coho salmon (*Oncorhynchus kisutch*); it is also the site of a state fish hatchery. Commercial timber harvesting, primarily of Douglas fir (*Pseudotsuga menziesii*), began in the mid-1950s with activities concentrated in the lower part of the basin on private lands. Peak harvesting rates occurred in the late 1960s, utilizing techniques that produced severe environmental damage in several tributary basins. These techniques included the construction of logging roads in channels, removal of timber from entire hillslopes, and absence of buffer strips from channel boundaries. Since then, improved management techniques have been employed and the rate of harvesting has slowed, though no detectable decline in the rate of landsliding was noted as a result (McHugh, 1986).

METHODS

Air photo interpretation provides a relatively quick and inexpensive means of reconstructing historical channel conditions over large basins. The RAPID technique uses changes in patterns of open riparian canopies observed on air photos of forested basins to detect changes in channel conditions and link them with possible upstream causes. Due to the difficulties of identifying channel changes under dense riparian canopy, the main criteria used in interpretation is riparian canopy opening or change in width of open reaches. As such, RAPID is only able to detect disturbance that removes streamside vegetation; it does not detect aggradation or degradation when streamside vegetation is not affected, minor shifts in channel location, or minor changes in channel geometry (Grant, 1988).

The upstream sources and downstream patterns of open reaches and the links between them were used to evaluate the effectiveness of different physical processes in generating downstream effects. Two assumptions inherent in this evaluation are that: (i) different processes produce different patterns of opening and (ii) the pattern of opening downstream is distinctive enough to indicate the type of disturbance that produced it. These assumptions proved valid in studies in the Western Cascades of Oregon (Grant et al., 1984) though more strongly for debris flow sources than for peak flows and surface erosion (Grant, 1986).

The sources, patterns, and linkages of open riparian canopies were characterized by measuring the distribution and area of open reaches directly from air photos. Photographs were viewed using a mirrored stereoscope with magnification of 2× and 4×. All photo work was done under stereo to define the channel boundaries more accurately and overcome shadow effects. Interpretation was limited to the center of the photograph to minimize the effects of edge distortion. Distances were measured using a photo scale marked on a clear mylar strip and an eye loup marked with a scale in tenths of millimeters.

Table 1. Years, scales, and types of air photos used in study.

Year	Scale	Type	Used in RAPID inventory?
1940	1:40 000	black and white	no
1956	1:12 000	black and white	yes
1964	1:12 000	black and white	yes
1969	1:15 840	black and white	yes
1979	1:24 000	color	yes
1986	1:12 000	color	no

Channels exhibiting open reaches were measured beginning at the most upstream site of opening and moving downstream. Initial sites of opening were classified by whether they headed at a landslide or ravel slope, or at a clearcut, road, or forest with no landsliding evident. Widths of open reaches were sampled at 100-m intervals, beginning at the upstream end of an opening and stopping at the downstream end of the continuously open reach. Unopened reaches had no width measurement, but lengths were included in the total measure of channel length. The location of landslides, tributary junctions, road crossings, clearcuts, and other influences were noted where they intersected channels. Distances between two known points were compared between photo intervals as a check on accuracy; a 10% difference was allowed for photo measurement error. Since all distances were within this error range, it is assumed that measured values were within 10% of the true value. The smallest open reaches which could be detected on a 1:24 000 scale photograph were 10 m long.

The specific processes that created open reaches were interpreted from a series of physical parameters identified and measured on the air photos. These included the: (i) presence or absence of mass movement at the initial site of opening; (ii) change in width downstream from the initial site of opening; (iii) degree of spatial continuity between the initial site of opening upslope and subsequent opening downstream; and (iv) total area of continuously open reaches downstream (Grant, 1988). Open reaches inferred to be initiated by landslides or debris flows were identified by a headscarp at the initial site of opening, long to moderately long continuously open reaches, and generally decreasing widths of opening downstream. Open reaches inferred as resulting from surface erosion were identified by small or nonexistent headscarps, continuously open reaches of variable length, and generally decreasing widths downstream. Open reaches assumed as resulting from peak flows had no identifiable source of sediment and debris, exhibited variable-sized patches of opening, and generally increased or remained constant in width downstream. Linkages between upslope forestry activities and downstream channels were recognized by whether: (i) open reaches extended continuously between upslope forestry activity and channels downstream; and (ii) the degree and timing of opening in higher-order channels coincided with the levels and timing of harvesting in upstream basins, where continuous opening from low-order tributaries was not apparent.

Air photos taken in 1956, 1964, 1969, and 1979 (Table 1) were used to reconstruct the overall disturbance history of 10 third-order or larger tributaries to Elk

Table 2. Stream order, drainage area, type of investigation conducted, and presence or absence of forestry activity and open reaches on 10 tributaries to Elk River, 1956–1979.

					1956§		1964§		1969§		1979§	
No.†	Tributary name	Order	Area (km²)	Type of‡ investigation	Open reach	Clearcuts/ roads	Open reach	Clearcuts/ roads	Open reach	Clearcuts/ roads	Open reach	Clearcuts/ roads
1	S. Fork Elk	4	19.4	1,2	Y	N	Y	Y	Y	Y	Y	Y
2	N. Fork Elk	4	24.5	1,2,3	Y	N	Y	Y	Y	Y	Y	Y
3	Blackberry	3	12.4	1	N	N	N	Y	N	Y	N	Y
4	Milbury	3	2.5	1	N	N	N	Y	Y	Y	Y	Y
5	Bulter	5	18.0	1,2	N	N	Y	Y	Y	Y	Y	Y
6	Panther	5	23.6	1,2,3	Y	Y	Y	Y	Y	Y	Y	Y
7	Red Cedar	4	7.7	1,2,3	Y	N	Y	N	Y	N	Y	N
8	Purple Mtn.	3	4.0	1	N	N	Y	Y	Y	Y	Y	Y
9	Bald Mtn.	4	27.6	1,2	Y	Y	Y	Y	Y	Y	Y	Y
10	Anvil	3	7.1	1	Y	Y	Y	Y	Y	Y	Y	Y
Basins with open reaches or clearcuts and roads:					6	3	8	9	9	9	9	9
Basins with both open reaches and clearcuts:					3		7		8		8	

† Tributary number corresponds to location map, Fig. 3.
‡ 1 = Air photo survey recording presence or absence of clearcuts, roads, and open reaches; 2 = channels inventoried using RAPID technique; and 3 = field survey.
§ Y indicates presence of open reach, clearcut or road; and N indicates absence of open reach, clearcut, or road.

River (Table 2). The air photos showed channel conditions prior to extensive forestry activity in the basin as well as changing conditions due to timber harvesting and large storms. Of these, six fourth-order or larger basins were chosen, based on stream order and harvest history, for an intensive inventory using the RAPID technique, as described above. Five basins of these were harvested during the study period; a sixth unlogged basin in a wilderness area (Red Cedar Creek) was included in the inventory as a geomorphic benchmark or control. Air photos taken in 1940 and 1986 were also examined for a qualitative assessment of channel conditions, but were not included in the inventory due to differences in photo scale and limited availability of the photographs.

Sediment impacts on the main stem Elk River between the junction of North and South Fork Elk River and Anvil Creek were assessed from the change in number of gravel bars counted on the 1940, 1956, 1964, 1969, 1979, and 1986 air photos. Gravel bars were tallied by channel segment, using the junction of major tributaries with the main stem as segment divisions, so basins with different erosional histories could be evaluated (Fig. 3). Since the exposure of gravel bars is a function of stream discharge, flow data were checked to ensure comparable exposure between photo series. Flow discharge from the closest gauging station with a suitable record (South Fork Coquille River at Powers, OR) ranged from 0.74 m^3/s (26 ft^3/s) on the 1964 photos to 1.08 m^3/s (38 ft^3/s) on the 1979 photos. Elk River flows were assumed to be similar and comparable for the purposes of this investigation.

The change in number of gravel bars provided a surrogate measure of sediment impacts, assuming an increase in the number of bars indicated an increase in sediment production. Only the change in the number of gravel bars was assessed; the change in size of gravel bars was not measured in this investigation. Both lateral and mid-channel bars located in the unvegetated, active channel were included in the tally. Newly exposed gravel bars were counted as new gravel bars since devegetation of these surfaces indicated a change in channel conditions. Bars dissected by small stream channels were counted as one bar (or bar complex) when they occurred on one side of the channel and two bars when separated by the wider main channel. Braided channels were not apparent on the main stem Elk River in the areas examined.

In addition to the air photo inventory, a field investigation was conducted on three tributaries that had both open and closed reaches (Panther Creek, Red Cedar Creek, North Fork Elk River) to quantitatively define channel characteristics associated with opening. These channels were selected for this investigation because they each contain a wide, low gradient reach and have a high potential for increased sedimentation effects. If downstream effects were occurring, they would most likely be observed in these reaches. Panther Creek and North Fork Elk River are similar in size; Red Cedar Creek is considerably smaller in area but was included in this investigation because of its wilderness status (Table 2).

The width of the valley floor, defined as the distance extending perpendicular to the channel and spanned by surfaces less than 3 m in height from the low-flow datum, and the active channel surface, defined as the width of the unvegetated channel, were measured at 100-m intervals. A 3-m vertical cutoff was used to define the valley floor limits, since visual observations and the presence of mature ($>$100 yr old) vegetation indicated that surfaces higher than this had not been disturbed by historical flood flows. The longitudinal profile of the channel was surveyed by measuring the elevation gain and lengths at topographic slope breaks in the channel. Distances were measured using a 30-m tape and elevations were measured using a hand-held level and 9-m fiberglass rod.

RESULTS

The results are presented to describe how different portions of the basin responded to forestry practices. These include an analysis of the spatial and temporal distribution of channel changes in: (i) the entire basin, (ii) low (first- to third-)-order tributaries, (iii) higher (fourth- and fifth-)-order channels, and (iv) the main stem Elk River (sixth-order).

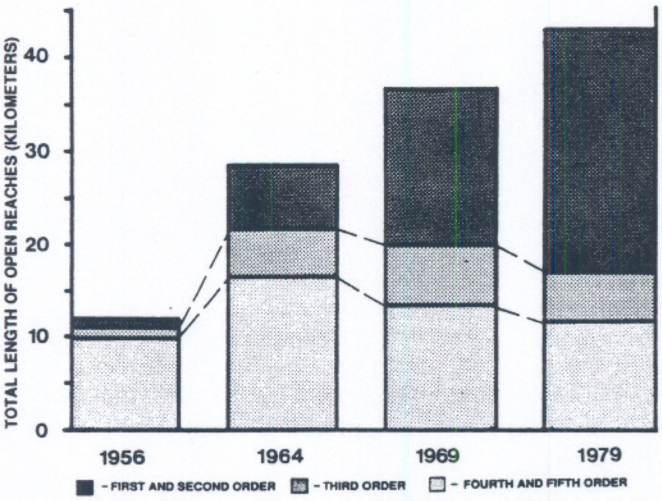


Fig. 4. Total length of open reaches in low-order tributaries and higher-order channels for four photo series.

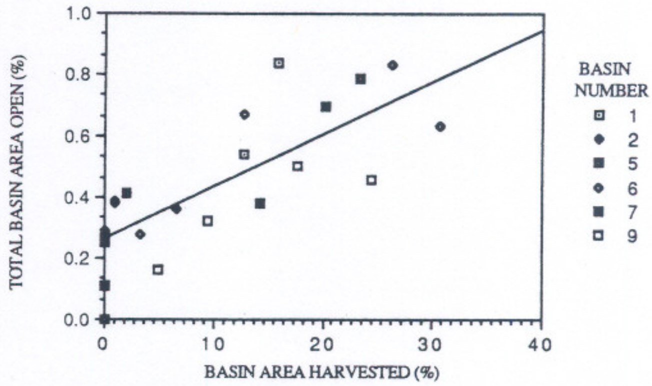


Fig. 5. Relationship between percent basin clearcut and percent basin open for six tributaries depicted on four photo series ($r^2 = 0.63$). Basin numbers refer to location map, Fig. 3.

Overall Pattern of Open Reaches

Open canopies occurred in both logged and unlogged basins; in 1956, open reaches were observed in six basins, three of which were unlogged, indicating open reaches may occur under natural conditions. However, the number of channels exhibiting open reaches increased concurrently with the increased level of clearcutting and road construction. By 1979, nine of 10 basins had been logged and all but one of the nine exhibited open reaches (Table 2).

The new openings were not uniform with respect to location within the drainage network (Fig. 4). Open reaches on the 1956 air photos were limited mainly to fourth- and fifth-order channels. On the 1964, 1969, and 1979 air photos, open reaches were located close to sites of forestry activity. Clearcuts and roads were concentrated along ridge-tops and midslopes and the greatest increase in new opening occurred primarily in low-order tributaries; the total length of open reaches in first- and second-order channels increased 30-fold between 1956 and 1979. There was a moderately strong correlation between the total area of basin harvested and the area of open reaches for all photo intervals sampled ($r^2 = 0.63$, SE = 0.14%) (Fig. 5). Fifty percent of the open channel lengths on all stream orders occurred adjacent to streamside clearcuts; as more of Elk River basin was clearcut, more channels bordered by clearcuts exhibited open reaches. Widening and open canopies were normally not detected immediately downstream from these clearcut sites, suggesting that disturbance associated with forestry activity did not travel far downstream.

Hillslope Processes and Open Reaches in Low-Order Basins

The largest increase in length of open reaches in low-order channels occurred between 1964 and 1969 and was attributed to the December 1964 storm. Most reaches opened during this period were due to landslides and surface erosion: 74% of the total number of open reaches were initiated by landslides while 20% were associated with surface erosion. Of these, 73% of the landslides and all of the surface erosion were also associated with clearcuts or roads.

Though landslides were the most common source of open reaches and, presumably, sediment and wood delivery to the channels, most landslides did not produce extensive lengths of open reaches. The average length of open reach from landslides which entered low-order tributaries was 240 m, with the longest open reach measured at 1170 m; most landslides produced open reaches in the 150 to 300 m range. By contrast, a similar study carried out in the Western Cascades of Oregon showed an average length of open reach from landslides to be 430 m, with the longest continuous opening extending over 13 km (Grant, 1986). These long openings were interpreted as resulting from debris flows or debris-laden floods. In the Knowles Creek basin of the Oregon Coast Range, 74% of the landslides produced debris flows that traveled over 400 m, with some extending 1600 m down channel (Benda, 1985). The short lengths of open reaches extending downstream from landslides in Elk River basin suggest that landslides in the basin do not generate long debris flows in comparison with other high relief areas in Oregon.

To determine the number of landslides generated in low-order basins reaching higher-order channels, a matrix analysis was conducted using the order where a landslide-initiated opening began and the order where the opening ended. Of the 100 landslides inventoried between 1956 and 1979, which initiated openings on first- and second-order channels, 77% ended on the same order they began (Fig. 6). The other 34% eventually reached third-order or larger channels. Half (17 of 34) of this latter category occurred in areas of Bald Mountain Creek underlain by quartz-diorite. Eleven landslides that initiated in first- or second-order basins reached fourth- or fifth-order channels, though most produced openings less than 100 m on the highest order channel; eight of these occurred in Bald Mountain Creek basin.

The above evidence suggests that, except for areas underlain by quartz-diorite, most channels in Elk River basin are not affected by long landslide or debris flow runout, since landslides from low-order basins are not connected to higher-order channels by continuously open reaches. Field evidence from a previous

Initial Stream Order \ Stopping Stream Order	1	2	3	4	5
1	51	11	10	9	1
2		15	2	1	0
3			15	1	0
4				20	0
5					4

Fig. 6. Matrix of stream orders that opening generated by mass movement begins and ends on as determined by continuously open reaches. The matrix is used to determine the number of landslides generated on tributaries of different order, which reached higher-order channels.

study supports this finding. McHugh (1986)[1] field-checked mass wasting sites in the basin, using debris levees, debris piled high on trees, and channels scoured to bedrock as evidence for debris flow activity. According to McHugh, while landslides occur throughout the basin, debris flow deposits are largely confined to areas underlain by quartz-diorite—roughly 10% of the total basin area. Hence, while debris flows do occur in Elk River basin, they are relatively uncommon due to the small percentage of land area underlain by a susceptible lithology. These findings corroborate with evidence in the present study that landslides from low-order tributaries do not generate long open reaches that connect with higher-order channels; this is likely due to the fact that landslides do not generate debris flows, based on evidence from McHugh's landslide inventory.

[1] We used the terms *debris flow* and *landslide* to correspond with the terms *debris torrent* and *debris slide* used by McHugh (1986).

Changes in Open Reaches in Higher-Order Channels

Though the number of open reaches on low-order tributaries continually increased during the study period, open reaches on fourth- and fifth-order channels in tributary basins did not change appreciably from the initial conditions seen in the 1956 photographs (Fig. 7). The percent of open fourth- and fifth-order channels was approximately the same in 1979 as in 1956. The proportion of total channel length that became or remained open between photo intervals ranged from 29 to 41%. Fifty-nine to 71% of the total channel length became or remained closed in each period. The amount of channel change between photo series, either new opening or canopy closure, comprised less than 20% of the total channel length for any given photo interval. Changes in the proportion of open channel length could not be correlated with the storms; in fact, in the photo period 1964–1969, which included the 1964 storm, the proportion of open channel length decreased slightly from 41 to 39%. Most opening during the period 1956–1979 occurred between 1956 and 1964, an interval without major storms. Since the change in opening and closing between photo series is close to the photo measurement error of 10%, some apparent change may be due to measurement error. The range of values, however, suggests that changes in lengths of channel exhibiting open reaches between photo series was small.

Changes in the pattern of open reaches were plotted by photo interval for the channel reaches observed in the field (Table 2), noting the location of newly opened and revegetated channel segments. Figures 8a and b depict the pattern exhibited in Panther Creek and Red Cedar Creek. Although the boundaries and area of opening varied somewhat between photo intervals, the

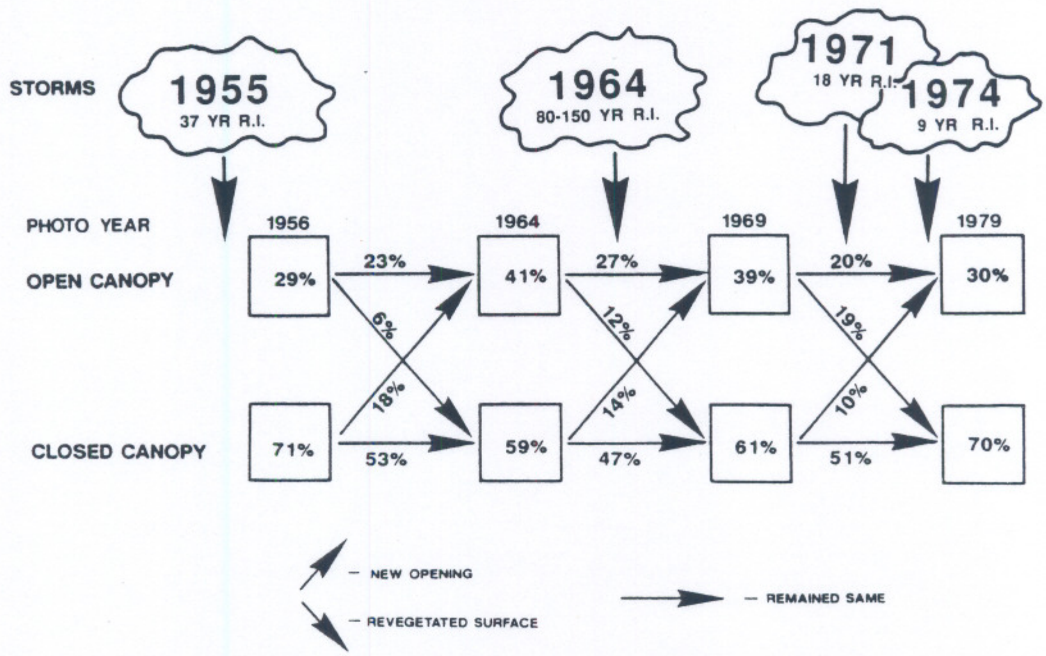


Fig. 7. Synopsis of change in channel length opened and closed between photo intervals for the fourth- and fifth-order segments of the six basins inventoried with the RAPID technique. Recurrence interval (R.I.) of storms indicated beneath year of event. The 1964 photos taken in summer before the occurrence of the 100-yr storm.

most striking change was an increase in width occurring during the period 1964–1969 followed by a decrease in width over the period 1969–1979. A longitudinal response, with opening proceeding progressively further downstream, was not observed. This latter type of response has been observed where a wave of sediment moving downstream produces channel widening and aggradation (Nolan and Janda, 1979; Lisle, 1982; Beschta, 1983a,b). Most downstream movement of opening was observed in the 1964 photos, prior to the December 1964 storm. In subsequent years only minor increases in open reaches downstream of previously opened reaches were noted. We speculate that increased widths of opening occur primarily during high peak flows, such as the 1964 storm, as flood waters scour and remove streamside vegetation. Widths of open reaches decrease in subsequent years as gravel bars and channel surfaces become recolonized by vegetation.

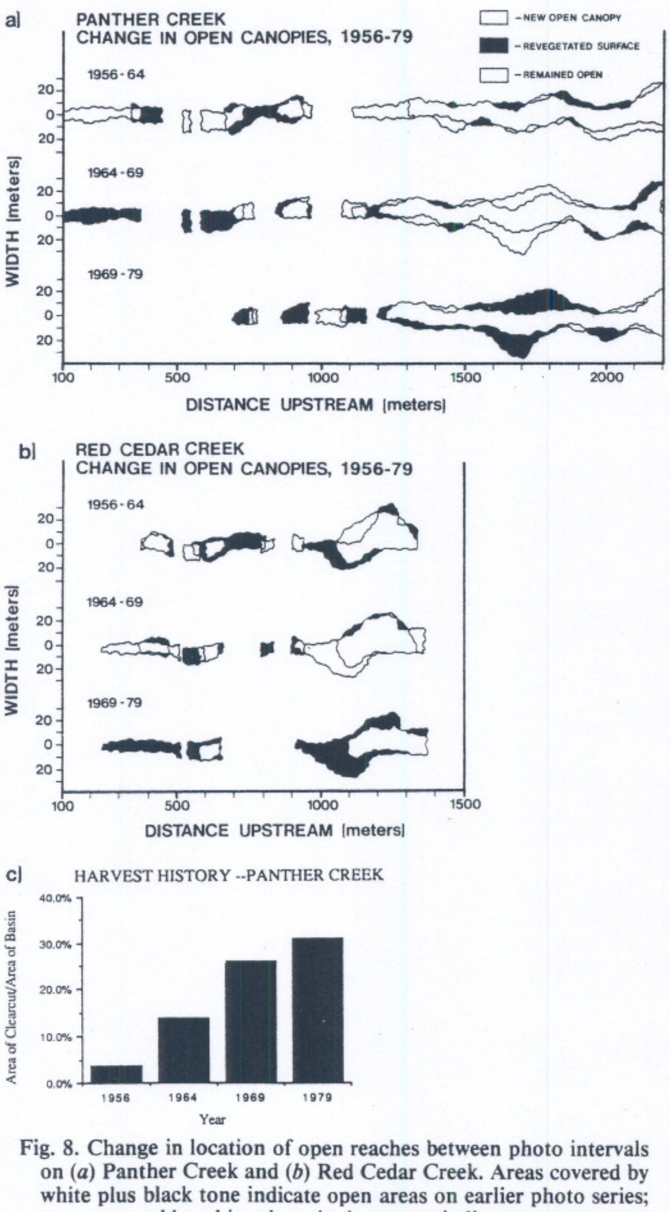


Fig. 8. Change in location of open reaches between photo intervals on (*a*) Panther Creek and (*b*) Red Cedar Creek. Areas covered by white plus black tone indicate open areas on earlier photo series; areas covered by white plus stipple pattern indicate open areas on latter photo series. Channel segments outside of mapped units are forested and did not change during photo interval. Measurement begins at juncture with main stem Elk River and moves upstream. First 100 m are not plotted as data has been smoothed using a moving mean; first and last values are not smoothed using this method and cannot be used for comparison. (*c*) Timing and percentage of Panther Creek basin clearcut between 1956 and 1979. Red Cedar Creek was not harvested.

Channel segments that remained opened throughout the study period were defined as chronically opened reaches. The locations of chronically opened reaches were coincident with channel segments that were both wider and had lower gradients than adjacent channel reaches. The Channel Morphology Index (CMI) was generated to quantitatively characterize the local width and slope of a channel relative to channel averages. The CMI is the product of two dimensionless indices:

$$\mathrm{CMI} = \mathrm{VFWI} \times \mathrm{SI}$$

where the valley floor width index (VFWI) is given by:

$$\mathrm{VFWI} = \frac{\text{Valley floor width}}{\text{Average active channel width}}$$

and the slope index (SI) is given by:

$$\mathrm{SI} = \frac{\text{Average channel gradient}}{\text{Local channel gradient}}$$

The VFWI measures the width of the valley floor relative to the average active channel width of the surveyed channel (1–2 km in length). To prevent one or two points from obscuring the pattern of the data, the valley floor width was smoothed prior to calculating the VFWI using a moving mean, averaging each data point with the preceding and succeeding value. The slope index is a ratio of the average gradient of a reach, measured 100 m above and below a sampling site, to the average gradient of the surveyed channel. The index measures the deviation from the average channel slope and can be used to compare streams with different absolute slopes. The SI was used instead of slope because it proved to be a more sensitive indicator of small changes in channel gradient than the slope itself. Because there was an inverse relationship between slope and valley floor width, the slope index was inverted prior to calculating the CMI to more effectively illustrate the relationship of both factors when compared to the distribution of chronically opened reaches.

Large CMI values correspond both with wide reaches unconstrained by valley walls (i.e., large VFWI values) and channel gradients less than average (i.e., SI values greater than one) as suggested by Fig. 9a, b, and c. Although the CMI is largely influenced by the value of the VFWI, there is also a good correspondence between large VFWI and SI values; 76% of the VFWI values greater than 3 are associated with SI values greater than 1 and 91% of the VFWI values less than 2 are associated with SI values less than 1.

The pattern and location of wide/low gradient and narrow/steep reaches was obtained by plotting the CMI as a function of distance (Fig. 9). The location of chronically opened reaches, obtained by overlaying

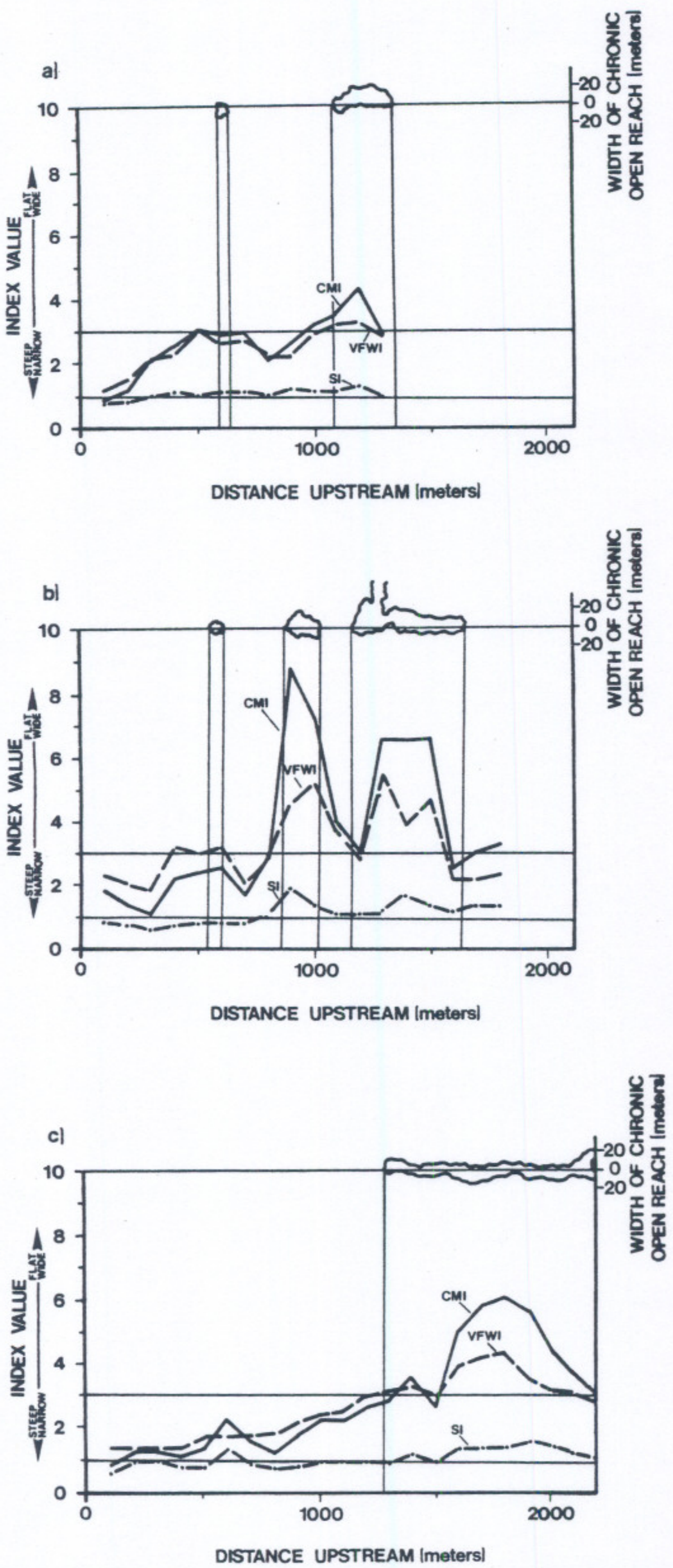


Fig. 9. Distribution of width of chronically opened reaches (defined as reaches opened throughout the study period), Valley Floor Width Index (VFWI), Slope Index (SI), and Channel Morphology Index (CMI) on three tributaries to Elk River: (*a*) Red Cedar Creek; (*b*) North Fork Elk River; and (*c*) Panther Creek. Top section of the graph shows width and location of chronically opened reaches while bottom of graph depicts the relationship and distribution of VFWI, SI, and CMI values. Vertical lines show location of chronically opened reaches relative to CMI values. Plotting techniques used in Fig. 8a and c also used here.

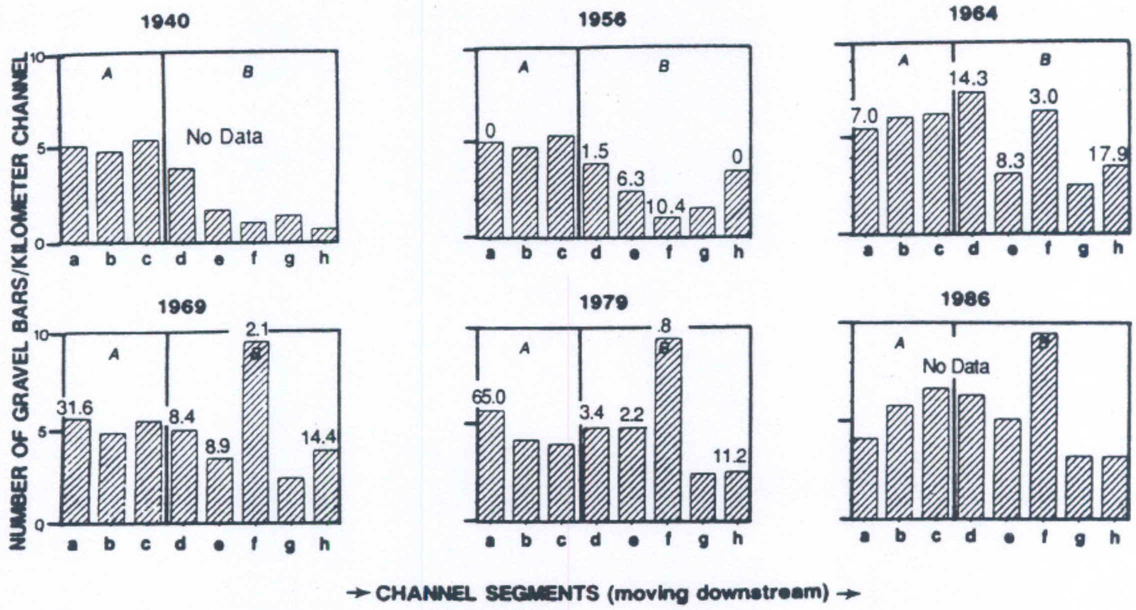
plots of open reaches between 1956 and 1979, is also shown. There is a good correspondence between the pattern of CMI values greater than 3 and the location of chronically open reaches in each of the three channels (Fig. 9a,b,c). Based on the relationships derived from the plots of the CMI values, approximately one-third of the surveyed channels exhibit chronically opened reaches and these are limited to wide/low gradient channels.

There was little correspondence between upslope forestry activity and opening downstream in the three channels surveyed—the timing and magnitude of opening was similar in all three channels, regardless of management history. Of the three, Red Cedar Creek was not clearcut or roaded and North Fork Elk River had less than 1% harvested until the last photo interval when 7% of the basin was clearcut. Changes in location or size of open reaches could not be attributed to the forestry activities in these basins since little or none took place. Conversely, Panther Creek basin was logged throughout the study period; a total of 30% of basin area was harvested between 1956 and 1979 (Fig. 8c). Despite this activity, the fifth-order channel (Fig. 8a) exhibited similar spatial and temporal patterns of opening as basins with little or no activity (Fig. 8b). The most significant increase in area of open reach occurred before 1964 and a general decline in area of open reach occurred after 1969 in all three channels.

Changes in Sediment Accumulation in Main Stem Elk River

A tally of the number of gravel bars on the main stem Elk River provided a coarse measure of sediment impacts for the period 1940–1986. Overall, there was a 77% increase in the number of gravel bars over a 26-km segment of the main stem Elk River. There was a greater increase in the number of bars in the lower end of the river compared to the upper end (Fig. 10). However, there was no correlation between the volume of material eroded in a tributary basin, as estimated from air photos and field checked by McHugh (1986), and the number of bars in the channel segment downstream from the junction with the main stem. The poor correlation may be due in part to the method of analysis, since only an increase in the number of bars was used to detect sediment impacts—no consideration was given to the change in size of existing gravel bars. It was noted that in wide/low gradient channel segments, the primary change in gravel bars was in size while change in number of gravel bars was favored in steep/narrow segments. Given that the main stem Elk River can be divided into two main parts, (i) an upper wide/low gradient segment and (ii) a lower narrow/steep segment, the more dramatic increase in number of bars in the lower segment may be biased because sedimentation effects in the upper segment may be under-represented due to an insensitive measure of gravel bar change. Changes in the number of bars is used here only as a qualitative indicator of potential sedimentation effects in the lower Elk River.

The most striking example of sedimentation effects on the main stem Elk River occurred below the junction of Purple Mountain Creek where landslides from harvested areas initiated debris flows that entered the main stem. Both channel widening and an increase in



Numbers above columns indicate the volume of material (in thousands of cubic meters) generated by landslides in tributary basins (from McHugh 1986).

Fig. 10. Number of gravel bars for individual segments of the main stem Elk River, 1940–1986. Segment *A* includes channel segment above junction with Butler Creek where reaches are generally wider and flatter, while Segment *B* includes channel segment below junction with Butler Creek where reaches are generally narrower and steeper, relative to the entire 26-km segment.

the number and size of gravel bars were observed in the main channel below this junction. Coarse material delivered by debris flows out of this tributary was deposited in the vicinity of a large bend in the main channel, where the velocity of the flows and channel competence decreased due to constriction immediately downstream.

Sediment impacts on the main stem Elk River below the Siskiyou National Forest boundary were examined qualitatively using air photos taken in 1940 and 1986. Channel changes were consistent with an increase in sediment deposition in this portion of the channel, including: (i) an increase in the number of gravel bars and size of existing bars; (ii) loss of riparian forest; and (iii) channel widening and an increase in width of active channel surfaces. This evidence suggests that the lower Elk River has become wider since 1940. How much of this change can be attributed to upslope forestry activities cannot be determined from this analysis, because the linkages between upslope harvesting and downstream canopy opening proved weak in intervening fourth- and fifth-order channels. Factors other than upstream logging, which may have influenced widening in this channel segment, include local agricultural and residential activity, local channel maintenance projects, logging on private lands on hillslopes above the channel, and cutting of the riparian forest adjacent to the channel.

DISCUSSION

In an address on the cumulative effects of forest management, Leopold (1981) stated, "To suppose that upstream changes in hydrologic parameters have no effect downstream flies in the face of principles of general physics on which modern science is built." Based on these principles it might be predicted that upslope forestry activities will ultimately affect the channels downstream. However, the magnitude of impacts can vary widely between basins due to differences in physical processes (Nolan and Marron, 1985). The results from this study suggest that channel changes due to forestry activity in Elk River basin were not as pronounced as in other Pacific Northwest basins. This may be due to the specific suite of erosional processes, channel morphologies, and distribution and timing of forestry activity in the basin relative to large storms, as well as to the techniques employed to detect the effects. These interactions are outlined below.

1. Lack of debris flow activity. Downstream effects were most prominent in tributary basins where harvest-related landslides generated debris flows. Debris flows are a rapid, voluminous, and highly erosive mode of sediment transport. However, widespread debris flows were uncommon in Elk River basin. Without debris flows, sediment transport occurs primarily by low-energy fluvial processes, which are less disturbing to channels and adjacent vegetation and less effective in producing open reaches. Absence of widespread debris flows limited direct delivery of landslide-derived material to higher-order streams. Much of this coarse material is presumed to be stored in low-order channels where it is being reworked by slower fluvial processes.

One reason why debris flows were not more widespread in Elk River basin is that the combination of types of mass wasting and drainage patterns were generally not conducive to long debris flow runout. In general, debris flows generated in basins with sharp or perpendicular tributary junction angles have relatively short runout lengths due to the abrupt change in channel direction and gradient promoting deposition at the junction (Benda, 1985). Areas of Elk River basin underlain by sedimentary formations have low tributary junction angles (20–30°) and a high potential for long debris flow runout. However, mass wasting in these areas is primarily by dry ravel and shallow, surficial slips; large debris slides capable of initiating debris flows are rare. Conversely, soils developed in areas underlain by quartz-diorite are noncohesive, have high permeability, and fail primarily as debris slides (Meyer and Amaranthus, 1979). However, tributary junctions in areas underlain by quartz-diorite are nearly perpendicular, as the drainage network is developed along a rectangular jointing pattern. Debris flows, when generated, tend to have short runouts, although some do reach higher-order channels.

2. Channel morphology limiting development of open reaches. The location of open reaches in higher-order channels was largely determined by the location of wide/low gradient channel segments. The potential for sediment accumulation is greater in these wide, flat reaches due to a deceleration of flows and a decline in shear stresses associated with channel widening and low stream gradients (Bull, 1979). Floodplains, terraces, gravel bars, and debris jams develop from accumulated sediment and debris in these reaches. These deposits are colonized by vegetation, which, in turn, is prone to disturbance during high flows and transport of sediment and wood. Debris jam failure and subsequent battering of riparian vegetation during high flows removes vegetation from channel surfaces, resulting in opening of the riparian corridor. Lateral channel migration across the valley floor, which can only occur in wider parts of the channel network, limits vegetation reestablishment along channel margins, producing chronically opened reaches.

Conversely, the potential for sediment deposition and floodplain development in steep/narrow segments is limited due to an increased channel shear stress associated with channel constriction and increasing channel gradients (O'Conner et al., 1986; Baker and Pickup, 1987). Because there is limited floodplain development in steep/narrow reaches, the stream directly abuts the steep valley wall and there is little room for riparian vegetation establishment. Channel boundaries hardened by bedrock offer little opportunity for channel widening and canopy opening. Because of this, narrow/steep segments rarely exhibit chronically opened reaches.

Most low-order channels and approximately two-thirds of higher-order channels in Elk River basin are steep and bedrock constrained. It is possible that sediment, water, and debris derived from upslope could move through these reaches without visible evidence in terms of changes in the canopy cover. Under these conditions there would be no visible spatial linkage between upslope forestry activities and downstream channel widening and aggradation in the wide, unconstrained reaches. If this were the case, then channel widening and open canopies should increase in the wide/low gradient reaches in relation to the level of upslope forestry activities. The evidence showed, however, that increased opening in wide/flat channel segments was not coincident with the timing or intensity of timber harvest. This may be due in part to an insufficient quantity of sediment produced by harvest-related landslides in comparison to the amount of sediment required for creating additional opening on wide/flat segments in the higher-order channels observed. For example, if the total volume of sediment generated from harvest-related landslides in Panther Creek between 1964 and 1969 (from McHugh, 1986) was spread over the wide/low gradient segment area downstream, a 0.3-m increase in depth would have occurred, assuming all material was deposited in this reach at one time. While this increase in sediment depth might have been enough to bury and kill some small trees in the riparian zone, it would not have been enough to create the widespread tree mortality necessary to produce a pronounced opening of the riparian canopy detectable on the air photos.

3. Low harvest intensities over much of the basin prior to the 1964 storm. The effects of the 1964 storm have been documented in basins throughout the Pacific Northwest and found to be severe and long-lasting. Record flows, massive landslides, and channel aggradation and widening occurred as a direct result of this event; timber harvesting and road construction appeared to be a factor contributing to the severity of response in many of the channels (Grant, 1986; Nolan and Marron, 1985; Lyons and Beschta, 1983; Lisle, 1981, 1982; Kelsey, 1980; Nolan and Janda, 1979; Stewart and LaMarche, 1967; and others). Unlike basins in the Pacific Northwest, which had been logged prior to 1964 and experienced major changes as a result of the storm, much of the Elk River basin was free from logging roads and clearcuts prior to this storm. The limited occurrence of landslides, debris flows, surface erosion, and open reaches at the time of the 1964 storm may have been due to the relatively pristine condition.

The most notable changes in downstream channel morphology following the storm occurred in Purple Mountain Creek and Butler Creek, two basins that had been altered extensively by forest practices prior to this event. Roads were built in or crossed channels and whole sections of hillslope were completely denuded of vegetation prior to the event. Though both channels exhibited downstream effects, the specific processes creating these effects were different. Landslides from harvested areas underlain by quartz-diorite in Purple Mountain Creek initiated debris flows that eroded channels as they moved through the drainage network; in Butler Creek, high sediment inputs from dry ravel and shallow landslides produced channel aggradation and subsequent opening downstream. The type of channel response exhibited in these basins, though striking, was not typical of the basin as a whole. This suggests that had more of the basin been altered by forestry activities at the time of the 1964 storm, channel response in Elk River basin may have been similar to that of other rivers in the Pacific Northwest.

4. Limitations of the air photo interpretation technique. Use of the RAPID technique in this study was considered experimental, as the assumptions behind the technique were based on processes in the Western Cascade Province of Oregon (Grant, 1988). Still, most of the assumptions appear to be valid since different sources of material produced different patterns of open reaches downstream. Landslides generated in the few areas underlain by quartz-diorite produced long, open reaches; field evidence from McHugh (1986) confirms that these open reaches occurred due to debris flows. Conversely, landslides and surface erosion in areas underlain by sedimentary and metamorphic rocks, which did not generate debris flows, produced only small, discontinuous openings. There was no evidence that peak flows in higher-order channels, in the absence of landslides, caused open reaches on a widespread scale.

The apparent decoupling between upslope disturbance and open riparian canopy downstream throughout much of Elk River basin, however, does not eliminate the possibility that downstream effects occurred. The RAPID technique only detects large-scale channel changes that disturb and remove riparian vegetation. Much of Elk River basin simply may not respond in a manner necessary for detection with this technique; lack of debris flows and channels constrained by bedrock limited the potential for opening. There may be other effects from forest activities, which did not disrupt the riparian vegetation and would require additional field work to identify. An increase in the number of gravel bars in the upper part and channel widening in the lower part of the main stem Elk River coincident with the timing of forestry activity suggests that some material delivered from tributary channels was deposited there, though perhaps not on the magnitude of other basins in the Pacific Northwest, where widespread channel aggradation, widening, and braiding occurred (Nolan and Janda, 1978, 1979; Lyons and Beschta, 1983).

SUMMARY

The original purpose of this investigation was to determine whether downstream effects produced by forestry activities could be detected in Elk River basin using air photo interpretation and to identify the processes that create those effects. Downstream effects were detected in low-order tributaries and produced mainly by landslides and debris flows from clearcuts and roads. However, changes in riparian canopy opening on most high-order channels could not be spatially or temporally linked to timber harvesting upslope. Similar spatial and temporal patterns of open reaches were observed in higher-order channels draining both logged and unlogged basins, with opening occurring mainly in wide/low gradient reaches. The increased delivery of sediment to low-order channels by landslides from harvested areas was, in a sense, decoupled both spatially and temporally from downstream channels in Elk River basin. An increase in the number of gravel bars coincident with forestry activities occurred in the main stem Elk River, but there was no correlation between the amount of sediment eroded in tributary basins and the number of gravel bars located downstream from the tributary junction.

According to Leopold (1981), changes in upslope land use will ultimately produce changes in channel regime downstream. However, only a limited sampling of higher-order channels in Elk River basin appeared to be affected by increased sediment delivered from upslope. The limited channel response observed here was attributed to three physical factors: (i) absence of extensive debris flows in most parts of the basin; (ii) channels constrained by competent hillslopes limiting the potential for opening; and (iii) low harvest intensities at the time of the 1964 storm. Whether or not downstream effects are detectable in a particular basin is, therefore, strongly influenced by the nature of the specific geomorphic processes and constraints operating in that system.

In addition, the specific processes active in Elk River basin may only be partly responsible for the observed decoupling of upslope and downstream areas as the limitations of detecting downstream effects from air photos were also recognized. Although observations made using the RAPID technique are consistent with field observations of key channel and hillslope processes made by McHugh (1986), our conclusion that there was not a strong linkage between upslope activities and downstream changes in channel condition must be taken with caution as there are limitations to the scale of resolution of the technique. RAPID only detects large-scale changes in channel geometry characterized by disturbance of riparian vegetation; other types of changes in volumes or distributions of sediment in channels cannot be detected with this method. Channels in Elk River basin may not respond to increased sediment delivered from upslope timber harvest on the gross scale needed to be detectable using the RAPID technique. Caution should be used when applying this technique in areas where the geology, climate, topography, vegetation, and land use vary greatly from those described here, as the specific processes generating downstream effects will be different.

Still, air photo interpretation proved useful in deciphering the gross disturbance history in Elk River basin and in distinguishing the general processes that generate downstream effects. Given the large-scale on which forest planning and environmental impact assessment takes place, this approach can assist researchers and land managers in identifying key geomorphic processes and interpreting disturbance histories particular to a landscape.

ACKNOWLEDGMENTS

This study was funded and supported in part by the Coastal Oregon Productivity Enhancement project (COPE)–Fisheries Enhancement Group, Oregon State University, and by Research Work Unit 4356, USDA Forest Service Pacific Northwest Research Station, Corvallis, OR. Nel Caine and three anonymous reviewers provided comments on earlier drafts of this paper, greatly improving its content. We would like to thank Margaret McHugh of the Siskiyou National Forest for use of her landslide inventory.

REFERENCES

Baker, V.R., and G. Pickup. 1987. Flood geomorphology of the Katherine Gorge, northern Territory, Australia. Geol. Soc. Am. Bull. 98:635–646.

Benda, L.E. 1985. Delineation of channels susceptible to debris flows and debris floods. p. 195–201. *In* Int. Symp. on Erosion, Debris Flows, and Disaster Prevention. Tsukuba, Japan. 3–5 September.

Beschta, R.L. 1983a. Long-term changes in channel widths of the Kowai River, Torlesse Range, New Zealand. J. Hydrol. (New Zealand) 22(2):112–122.

Beschta, R.L. 1983b. Channel changes following storm-induced hillslope erosion in the Upper Kowai Basin, Torlesse Range, New Zealand. J. Hydrol. (New Zealand) 22(2):93–111.

Bull, W.B. 1979. Threshold of critical power in streams. Geol. Soc. Am. Bull. Part 1 90:453–464.

Costa, J.E. 1984. Physical geomorphology of debris flows. p. 268–317. *In* J.E. Costa and P.J. Fleisher (ed.) Developments and applications of geomorphology. Springer-Verlag, New York.

Costa, J.E., and R.D. Jarrett. 1981. Debris flows in small mountain streams of Colorado and their hydrological implications. Bull. Assoc. Eng. Geol. 18(3):309–322.

Grant, G.E. 1986. Downstream effects of timber harvest activities on the channel and valley floor morphology of western Cascade streams. Ph.D. diss. Johns Hopkins Univ., Baltimore. (Diss. Abstr. 86-15958).

Grant, G.E. 1988. The RAPID technique: A new method for evaluating downstream effects of forest practices on stream channels. USDA-FS General Tech. Rep. PNW-GTR-220. USDA-FS, Pacific Northwest Res. Stn., Portland, OR.

Grant, G.E., M. Crozier, and F.J. Swanson. 1984. An approach to evaluating off-site effects of timber harvesting activities on channel morphology. p. 177–186. *In* Symp. on the Effects of Forest Land Use on Erosion and Slope Stability, Honolulu, HI. 7–11 May. Univ. of Hawaii, Honolulu, HI.

Karlin, R. 1980. Sediment sources and clay mineral distributions off the Oregon Coast. J. Sediment. Petrol. 50:543–560.

Kelsey, H.M. 1980. A sediment budget and an analysis of geomorphic processes in the Van Duzen River Basin, North Coastal California, 1941–75. Geol. Soc. Am. Bull. Part 2 91:1119–1216.

Leopold, L.B. 1981. The topology of impacts. p. 1–13. *In* Cumulative Effects of Forest Management on California Watersheds: An Assessment of Status and Needs for Information. Proc. of the Edgebrook Conference, Berkeley, CA. 2–3 June 1980. University of California, Berkeley.

Lisle, T.E. 1981. Recovery of aggraded stream channels at gauging stations in northern California and southern Oregon. p. 189–200. *In* T. Davis and A. Pearce (ed.) Erosion and sediment transport in the Pacific rim steeplands. IAHS Publ. 132. Int. Assoc. of Hydrological Sci., Oxfordshire, UK.

Lisle, T.E. 1982. Effects of aggradation and degradation on pool-riffle morphology in natural gravel channels, northwestern California. Water Resour. Res. 18:1643–1651.

Lisle, T.E. 1986. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, northwestern California. Geol. Soc. Am. Bull. 97:999–1011.

Lyons, J.K., and R.L. Beschta. 1983. Land use, floods, and channel changes: Upper Middle Fork Willamette River, OR (1936–1980). Water Resour. Res. 19:463–471.

McHugh, M.H. 1986. Landslide occurrence in the Elk and Sixes River basin, southwest Oregon. M.S. thesis. Oregon State Univ.

Meyer, L.C., and M.P. Amaranthus. 1979. Siskiyou National Forest soil resource inventory. USDA-FS, Pacific Northwest Region, Portland, OR.

National Climate Center, Environmental Data and Information Service, National Oceanic and Atmospheric Administration. 1983. Climate normals for the U.S. (Base: 1951–80). Gale Res. Co., Detroit, MI.

Nolan, M., and R. Janda. 1978. Summary of watershed conditions in the vicinity of Redwood National Park, California. Open-File Rep. U.S. Geol. Surv. 78-25.

Nolan, M., and R. Janda. 1979. Recent history of the main channel of Redwood Creek, CA: Cordilleran Group. p. x-1 to x-16. *In* A guidebook for a field trip to observe natural and management related erosion in Franciscan terrane of northern California. Cordilleran Section of the Geological Society of America, San Jose, CA.

Nolan, M., and D.C. Marron. 1985. Contrast in stream channel response to major storms in two mountainous areas of California. Geology 13:135–138.

O'Conner, J.E., R.H. Webb, and V.R. Baker. 1986. Paleohydrology of pool-and-riffle pattern development, Boulder Creek, Utah. Geol. Soc. Am. Bull. 97:410–420.

Stewart, J.H., and V.C. LaMarche. 1967. Erosion and deposition produced by the flood of December 1964 on Coffee Creek, Trinity County, California. U.S. Geol. Surv. Prof. Pap. 422-K. 22 pp.

Varnes, D.J. 1978. Slope movement types and processes. p. 11–33. *In* R.L. Schuster and R.J. Krizek (ed.) Landslides: Analysis and control. Trans. Res. Board, NAS, Spec. Rep. 176. National Academy of Sciences, Washington, DC.