

Logging-Related Increases in Stream Density in a Northern California Watershed¹

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Abstract

Although many sediment budgets estimate the effects of logging, few have considered the potential impact of timber harvesting on stream density. Failure to consider changes in stream density could lead to large errors in the sediment budget, particularly between the allocation of natural and anthropogenic sources of sediment.

This study conducted field surveys in randomly selected catchments in two managed and one old-growth watershed to determine the location of the channel's origins in the catchments. The drainage areas for identified channel heads were then delineated using a 1 m digital elevation model derived from laser altimetry. The two managed watersheds were heavily impacted by previous logging activities, particularly by tractor operations used to yard the timber out of the watersheds. The channel heads in the managed watersheds had smaller drainage areas than channels in a nearby old-growth watershed. The management activities led to a tripling of the drainage density in the managed watersheds.

Timber harvesting and the construction of skid trails used to transport timber to the road system led to increases in peak flow, ground water interception, soil compaction and drainage diversion, which reduced the drainage area necessary to initiate stream channels. Furthermore, it appears that recent ground-based yarding operations have further extended stream channels upslope, potentially creating additional sources of sediment for downstream receptors. Although these results may be unique to these watersheds, the changes in drainage density due to management activities found here emphasize the need to compare managed watersheds with undisturbed watersheds before using the current drainage network as a base-line for estimating chronic sources of sediment like bank erosion.

Key words: channel incision, drainage density, sediment budget

Introduction

Many watersheds in northern coastal California have been impaired by sediment discharges from non-point sources, particularly sediment sources related to logging activities. Efforts to assess the sediment impairment often include the construction of sediment budgets to create an “accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin” (Reid and Dunne 1996). Sediment budgets identify sediment sources and provide estimates of sediment delivery which can help prioritize erosion control efforts.

The extent of the stream network, or the drainage density, plays an important role in developing sediment budgets. Stream maps are needed to determine if discrete

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features (for example, landslides) have delivered sediment to the network. The drainage density is also important for estimating sediment delivery from diffuse sediment-generating processes (for example, bank erosion). Topographic maps do not include the majority of headwater streams and is a particular problem in areas under forest canopy (Benda et al. 2005). Therefore, field surveys are conducted to determine the extent of the stream network in the watershed (Montgomery and Foufoula-Georgiou 1993). However, stream lengths may increase due to forest management activities, and estimated drainage densities based on only the current stream network could overestimate the natural drainage density. If the current stream distribution is used to estimate natural chronic sources of sediment and the stream network is more extensive than it had been prior to disturbance, the impacts of timber harvesting will be underestimated.

The point of transition from an unchanneled swale, also known as a zero-order basin (Dietrich et al. 1987), to a channel is referred to as the “channel head.” The channel head is the upstream limit of concentrated water and sediment transport between definable banks. Knighton (1998) describes five processes related to channel initiation: two by overland flow (Horton overland flow and saturation overland flow) and three by subsurface flow (seepage erosion, tunnel scour and shallow landsliding). These processes are not mutually exclusive, and all may be present even in a relatively homogenous landscape. However, landsliding is likely to predominate in steep areas, while overland flow and seepage erosion predominate in lower-gradient areas. The location of the channel head is affected by climate, with wetter regions needing smaller drainage areas (Montgomery and Dietrich 1988).

Hillslope gradient can also influence channel initiation. Montgomery and Dietrich (1988) reported inverse relationship between drainage area and valley gradient, especially where landslides initiated channels. Channel heads initiated by overland flow may also reflect a relationship between drainage area and gradient relationship (Montgomery and Foufoula-Georgiou 1993), as may those of gullied channels (Vandekerckhove et al. 2000). However, there are circumstances where there is no relationship between drainage area and slope (Jaeger et al. 2007, Wemple et al. 1996). Dietrich et al. (1987) noted no systematic drainage area-slope relationship at sites in Oregon where channel head locations were thought to be controlled by the flow paths through fractured bedrock.

Since the drainage area needed to initiate channels depends on climatic conditions, it seems reasonable to expect that management activities that increase runoff may also decrease the drainage area and hence increase the drainage density. Roads increase runoff because road surfaces have lower infiltration capacity than natural slopes. The drainage area needed to support a channel head is smaller for drainages receiving road runoff (Montgomery 1994, Wemple et al. 1996).

Logging is also likely to have an effect on channel head location. Prosser and Soufi (1998) observed gully initiation during large rainfall events following forest clearing. Increases in peak flow due to a reduction in evapotranspiration (Lewis et al. 2001) likely plays a role in modifying channel head locations. Increases in peak flow could exceed the thresholds related to the channel initiation processes and decrease the drainage area for channel initiation.

In a comparison between cable-yarded clearcuts and old-growth forest, Pacific Watershed Associates (1999) found that valley catchments served as groundwater

reservoirs in old-growth areas, with most runoff carried through a network of interconnected subsurface pipes. The incised channels or gullied swales within the old-growth areas are discontinuous, inactive, and located much farther downstream (in other words, have larger drainage areas) than those identified in the clearcut drainages of the harvested areas. Pacific Watershed Associates concluded the swales in logged areas had experienced gullying in response to first-cycle harvesting.

This study seeks to determine the effects of logging on stream network by comparing the stream density in two logged watersheds with a nearly pristine watershed. The field surveys also identified the channel initiation processes and the management features associated with channel heads. This information will be used to determine if the drainage density can be estimated from drainage area alone or from a drainage area-slope relationship.

Methods

In Elk River watershed, located near Eureka, California, three subwatersheds were surveyed to determine the catchment area needed for channel initiation and to examine the influence of valley gradient on the location of channel heads. These watersheds share similar bedrock, which primarily consists of the sedimentary rocks with a sheared and highly folded mudstone exposed in the deeper portions of the canyons of the watersheds. The three watersheds have average hillslope gradients of 23° to 24°. These watersheds experience a Mediterranean climate with dry summers and wet winters and with an average annual precipitation of 1650 mm. Forest stands in Elk River are dominated by redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) (Buffleben 2009).

The primary difference between the three watersheds is their management history. South Branch North Fork Elk River (SBNFER) watershed was first logged in the 1970s, though small areas were harvested in the 1940s and 1960s. The western portion of the Corrigan Creek (CC) watershed was first logged in the 1950s and the eastern portion in the 1970s. These harvests were primarily clear-cut and tractor yarded on an extensive skid trail network. Measurements on air photos indicate the skid trail density is 32.9 and 31.4 km/km² in SBNFER and CC respectively. Both of these watersheds experience ongoing logging entries beginning in the late 1980s, consisting of partial-cut and clear-cut harvests with tractor yarding. The portion of the Little South Fork Elk River (LSFER) surveyed in this study is primarily an old-growth redwood forest, although a 2.3 km road was constructed in the 1990s and decommissioned in 2003.

Since it is impractical to conduct surveys of the entire watershed for even these relatively small watersheds, the watersheds were divided into catchments from which a random selection of catchments was surveyed. Catchments within the three watersheds were delineated from a 1-m digital elevation map (DEM) derived from laser altimetry. 12 to 14 percent of the watersheds were surveyed between October 2005 and May 2006. Based on a nearby rain gauge located in Eureka, the inspections occurred during a wetter than average winter period (148 cm of rainfall, 58 percent greater than the average annual precipitation).

Field crews were provided large scale maps (typically 1:4000) of the catchments. Typically, field crews would hike up all swales and traverse other areas in the

catchments to locate channels heads. Channel heads were defined as the farthest upslope location of a channel with well-defined banks (Montgomery and Dietrich 1988). Since stream channels typically begin as discontinuous segments and access to portions of the catchments was difficult due to thick vegetation and old logging debris, some subjectivity is introduced in identifying channel heads. The locations of the channel heads were recorded using Global Positions System (GPS), although if GPS reception was poor, a laser range finder was used to determine the distance to a known location (for example, a road or tributary junction). Along with the location, other attributes recorded included slope (as measured with a clinometer to a point approximately 5 m above the channel head), type (for example, spring, head cut), and management activities (for example, presence of roads, skid trails, yarding corridors, stand age). The drainage area for a channel head was defined as the upslope area draining into that feature as delineated on the 1 m DEM. Further details on the field methods and data analysis are included in Buffleben (2009).

Results

For the managed watersheds, SBNFER and CC, channel heads were found in most of the catchments and several catchments in these watersheds had multiple channel heads (*table 1*). Catchments without channel heads in the managed watersheds were small and didn't have a major drainage axis or swale within their boundaries. It is likely that the limited drainage area in these catchments prevented erosion thresholds from being exceeded. Most channel heads in the managed watersheds were associated with some type of management feature, the most common of which are skid trails. This result is not unexpected considering the high skid trail density in these watersheds. Seepage erosion and saturation overland flow are important channel-forming processes along road and skid trail cutbanks. Tunnel scour is also commonly associated with skid trails. Landslides appear to be a minor process in channel-head formation in these watersheds.

Table 1—Number (and percentage) of catchments with channel heads and number of channel heads with identified management associations.

	South Branch North Fork Elk River	Corrigan Creek	Little South Fork Elk River
Catchments with channel heads	15 (94%) ^a	11 (65%)	6 (43%)
Number of channel heads	22	17	6
Road cutbank	2	1	2
Road landslide	1	-	-
Landing tunnel scour	1	-	-
Skid trail cutbank	5	4	-
Skid trail tunnel scour	8	2	-
Channel heads with identified management association	17 (77%) ^b	7 (41%)	2 (33%)

^a Percent of catchments with channel heads.

^b Percent of channel heads with identified management association.

The range in drainage area at the channel heads exceeds an order of magnitude (*fig. 1*). The average drainage size in these watersheds is 0.69 ha and 0.98 ha and the median is 0.42 and 0.72 ha for SBNFER and CC respectively. Catchments in LSFER are separated into two categories depending on whether or not the road passed through the catchments. Results for the five catchments that contain portions of the road are similar to those from the other managed watersheds. Three small catchments (averaging 0.6 ha in size) did not have channel heads. For the two catchments with channels, the channel heads were clearly associated with the road and the drainage areas for these channel heads reflect the road location in the catchment.

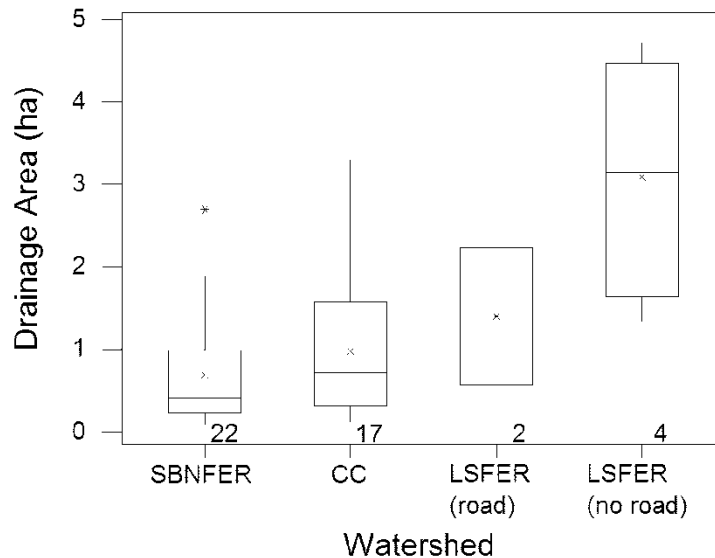


Figure 1—Box plot of drainage area of the channel heads. The number of channel heads in each group is shown above its name. The median (50th percentile) is marked by the center line within the box and the mean is shown as an X. The whiskers extend to the values that fall within 1.5 * IQR (interquartile range). Outliers are plotted with asterisks (*) when they fall outside of this range.

Nine catchments within LSFER were not affected by the road construction. Five of these catchments had no channels. While three of these catchments were small and did not have swales, two catchments were very large with drainage areas of 4.85 and 5.29 ha. These two large headwater catchments without channel heads exceeded the drainage area for the four catchments with identified channel heads, which had average and median drainage areas of 3.10 and 3.15 ha respectively. It appears that the area of the two large catchments without channel heads is below the erosion thresholds necessary to initiate a channel head. If so, it seems appropriate to include the area of these two catchments as a minimum value in determining the drainage area needed to initiate channels in the undisturbed portions of LSFER. Including these two catchment areas raises the average and median drainage area to 3.75 and 4.22 ha respectively.

The median drainage areas for channel heads in SBNFER and CC are significantly different than that for LSFER (Mann-Whitney test, $p = 0.0062$ and 0.0138 respectively). Furthermore, the p -values decrease when the two large catchments without channel heads were included in the LSFER. The drainage areas for the managed watersheds, SBNFER and CC, were combined and the median drainage area was used to construct estimated stream networks for managed conditions in the three watersheds. Likewise, the median drainage area for undisturbed catchments in LSFER, including the two large catchments where channel heads were not present, was used to construct stream networks for old-growth forested conditions in the three watersheds. Stream networks for forested and managed conditions were then compared to estimate the drainage density resulting from the timber management. The drainage density in the managed forests was to 2.7 to 3.1 times the natural drainage density.

To test for a relationship between slope and drainage area, regression analysis was conducted using the log-transformed drainage areas, since the drainage areas were not normally distributed (Anderson-Darling normality test, $p = 0.000$). Using all the channel head data in the regression analysis resulted in a poor, insignificant relationship, which indicates that slope is not a dominant factor in determining drainage density in these watersheds.

Discussion

Our surveys in the unaltered portions of the old-growth forest indicate that subterranean soil pipes play an important role in the transportation of stormflows, since infiltration rates are high and overland flow rarely occurs in undisturbed forested watersheds. We observed and measured several soil pipes at the channel heads (approximately 15 cm in diameter). It appears that soil pipes form a well-developed subterranean network and are stable enough to carry stormflows large distances downstream. Erosion thresholds are eventually overcome when several unchanneled swales merged. Timber management activities appear to have destabilized the soil pipe network and dramatically reduced the drainage area needed for channel initiation, thereby increasing the drainage density. Two aspects of management may have been particularly influential: the construction of roads (and skid trails) and the removal of vegetation. The increases in drainage density observed in these watersheds are greater than those found in previous studies (Montgomery 1994, Wemple et al. 1996). The large increases identified here may be due in part to the extremely high density of skid trails. Although only used briefly during a harvest cycle, skid trails have similar impacts as roads in that they intercept ground water, increase runoff due to ground compaction, and change drainage patterns. Skid trails were observed at many of the channel heads (*table 1*). Observations suggest that soil compaction on skid trails may play a role in tunnel scour and roof collapse in soil pipes.

The reduction in drainage area for the channel heads may have other contributing factors other than the presence and impacts of skid trails. Many of the channel heads in the logged watersheds were not associated with management features (*table 1*). Vegetation removal is likely to have reduced the drainage areas for channel heads through several mechanisms. Vegetation removal increases runoff due to reductions in transpiration and interception (Lewis et al. 2001). The increased runoff can

destabilize the soil pipes and form gullies (Reid et al. 2010). Another factor that may contribute to destabilization of soil pipes is the reduction in root strength, which could decrease soil cohesion and resistance to erosion.

This study did not observe an inverse drainage area-slope relationship. One possible reason for the lack of this relationship may be the significant scatter in drainage area for a particular slope, thereby making it difficult to observe a trend (Jaeger et al. 2007). Also, it is possible that the range of slopes was too narrow to detect a slope-area relationship. Landslides, typically occurring on steep slopes, are present in these watersheds. However, only one channel head in these surveys was associated with a landslide. The lack of landsliding may indicate that these watersheds lacked significant portions of steep slopes, which would diminish the ability to detect a drainage area-slope relationship. However, a trend regarding the drainage area-slope relationship was observed. As the drainage areas have been reduced by management activities, channel heads have moved closer to ridgelines, where swale-axis slopes are steeper.

The increase in drainage density observed in these watersheds is important to consider during construction of sediment budgets. An increase of drainage density suggests greater peak flows which could add to channel erosion and sediment yields. Furthermore, if a sediment budget used the existing drainage density to estimate the sediment delivery from soil creep, it would be overestimate the sediment delivery from this natural process.

Furthermore, it is clear that in the past large amounts of sediment have been delivered to the stream network due to the shift in location of the channel head (Pacific Watershed Associates 1999). These relatively new channels, caused by management activities within the last 100 years, may still be unstable and are potentially chronic sediment sources due to continued headcutting and bank erosion occurring within the channels (Reid et al. 2010).

In several catchments in the Corrigan Creek watershed that had recent timber harvesting operations, we observed the upslope migration of channel heads. These channels appeared to be intercepting groundwater flow from skid trails used in the recent logging operations. However, these newer channel heads may only be temporary seeps that are due to the increased runoff associated with the harvest. Also, since our surveys took place during a wetter than average year, the new channels may not become permanently established or become chronic sources of sediment.

Given that water quality is impaired in the Elk River watershed and that it is extremely difficult to manage gully erosion once it has initiated, steps to prevent upslope migration of channel heads should be considered when developing plans to mitigate the impacts of future logging. Tractor operations and construction of new skid trails should be minimized along a swale axis. Furthermore, to reduce the increases in peak flows and loss of cohesion due to vegetation removal, partial-cuts should be considered instead of clear-cutting in well-defined swales.

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