Effects of Recent Logging on the Main Channel of North Fork Caspar Creek[1]

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Abstract: *The response of the mainstem channel of North Fork Caspar Creek to recent logging is examined by time trends in bed load yield, scour and fill at resurveyed cross sections, and the volume and fine-sediment content of pools. Companion papers report that recent logging has increased streamflow during the summer and moderate winter rainfall events, and blowdowns from buffer strips have contributed more large woody debris. Changes in bed load yield were not detected despite a strong correlation between total scour and fill and annual effective discharge, perhaps because changes in stormflows were modest. The strongest responses are an increase in sediment storage and pool volume, particularly in the downstream portion of the channel along a buffer zone, where large woody debris (LWD) inputs are high. The association of high sediment storage and pool volume with large inputs of LWD is consistent with previous experiments in other watersheds. This suggests that improved habitat conditions after recent blowdowns will be followed in future decades by less favorable conditions as present LWD decays and input rates from depleted riparian sources in adjacent clearcuts and buffer zones decline.*

North Fork Caspar Creek (NFCC) provides a rare opportunity to observe the effects of altered inputs of all of the important watershed products (water, sediment, and woody debris) to which forested stream channels respond after logging. Understanding the effects of recent experimental logging requires first an understanding of the background influences of basin geomorphology, hydrology, and bedrock and the legacy of old-growth logging done in the late 19th century (Napolitano, these proceedings). We also need to understand the mechanisms for channel change that are affected by altered inputs of water, sediment, and woody debris that originate from hillslopes, headwater channels, and riparian areas that were disturbed by recent logging. Finally, we need to understand stream conditions that are critical to aquatic fauna (e.g., salmonids and herpetofauna) and other water-resource issues in order to evaluate the importance of channel responses.

North Fork Caspar Creek: Modern Channel Conditions

The Main Channel

North Fork Caspar Creek is a steep, perennial, gravel-bed channel typical of low-order streams draining second-growth, coastal redwood forests of central and northern California (*table 1*). Its valley flat, which is 6 to 20 m wide, is confined between steep (≥70 percent), inner-gorge hillslopes where evidence of landslide activity is common (Cafferata and Spittler, these proceedings). Most of the valley flat is occupied by forested, gravelly terraces that stand a meter or more above the channel bed and are rarely, if ever, flooded (Napolitano 1996). Their origin will be discussed later.

The bed of the main channel (Stations LAN to ARF; Preface, fig. 2, these proceedings) commonly consists of a thin (<0.5 m) layer of cobbles, gravel, and finer material overlying bedrock, which is intermittently exposed (*fig. 1*). Much of this bed is composed of a framework of coarse colluvium or lag material (large, angular cobbles and boulders that remain as deposited by streamside landslides and debris flows). This material is too coarse to be moved

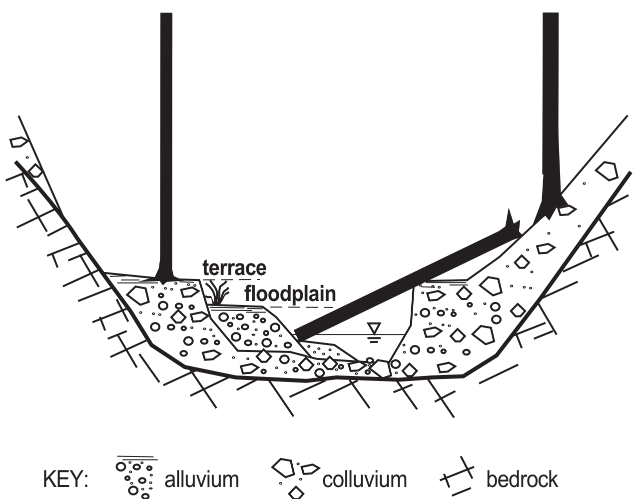

Figure 1—Idealized cross section of the mainstem channel of North Fork Caspar Creek. "Colluvium" is debris flow deposits.

Table 1*—Dimensions of North Fork Caspar Creek near Station ARF.*

Drainage area	380 ha
Order	3[a]
Channel gradient	0.02
Mean annual discharge	0.092 m^3s^{-1}
Bankfull discharge	5.4 m^3s^{-1}
Mean bankfull width	7.7 m (2-12 m)
Mean bankfull depth	0.6 m

[a]Determined from 1:24,000 topographic map and including non-blue-line channels.

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by even the largest floods; it helps stabilize the bed but also inhibits scour of deep pools and makes much of the channel unsuitable for spawning. Bars of alluvium (rounded gravel and sand transported by streamflow) overlie the lag material near large landslides and tributary junctions, upstream and downstream of woody debris jams, and in reaches widened by debris-induced bank erosion. The highest bars are capped with fine sediment (silt and fine sand) and herbaceous vegetation, and grade into active floodplains (surfaces which are flooded once every other year or so). Bars furnish the bulk of the bed load transported during peak flows. Fine bed load (sand and fine gravel) is stored in pools and transported during modest peak flows that are too weak to mobilize channel armor (single layers of gravel and cobbles capping more mobile bed material).

Sediment Sources

Sediment in Caspar Creek is derived from the Coastal Belt Franciscan Assemblage (Kramer 1976) which in this basin consists mostly of moderately fractured and weathered, interbedded, greywacke sandstone and shale. This material is highly erodible. Deep weathering has produced fine-grained soils and soft colluvium that readily decompose to fine material (silt and fine sand) during erosion and transport.

Streamside landslides that border much of the valley flat of the mainstem channel are large but infrequent sources of sediment. In 1974, for example, a landslide (3,300 m^3) entered the North Fork channel, and another entered the South Fork (600 m^3); their volume equaled 56 percent and 42 percent, respectively, of the total sediment yield for that year, although not all of the landslide material reached the downstream measurement stations (Rice and others 1979). These types of shallow landslides from the inner gorge are merely the surficial erosion of the toes of much more extensive and deeper, rotational failures (Cafferata and Spittler, these proceedings). Disturbance of inner gorges by logging or road building could increase surficial landsliding, but it is unlikely that the larger-scale failures would be affected.

Another source of sediment is gullies and debris flows that erode colluvium filling low-order valleys and unchannelized swales. We have not witnessed a significant debris flow since establishment of the experimental watershed, but much of the valley fills and deltas at the mouths of small tributaries were apparently deposited by debris flows (Napolitano 1996). More chronic sediment sources are enlargement and collapse of soil pipes leading to gully erosion of low-order valley fills (Keppeler and Brown, these proceedings). Logging of old-growth forests and loss of large chunks of woody debris that would buttress these deposits in swales may have accelerated this process. Increased and diverted runoff from roads during intense rainstorms could promote gullying and debris flows, but since the roads in NFCC basin are located near ridges, this has not been an important process.

Bank erosion and net scour of the active channel of the mainstem is a minor source of sediment overall, but a major source of gravel. From 1980 to 1988, channel scour accounted for only 13 percent of the yield of total sediment, but 42 percent of the gravel (Napolitano 1996). Most gravel (>90 percent) came from sediment stored in the active channel rather than from bank erosion.

The bulk of the sediment in NFCC (70 percent) is transported in suspension as silt and fine sand; the remainder is transported as bed load of sand and gravel. This means that most of the sediment reaching the mainstem has little effect on channel processes but instead is carried out of the basin with the flow. A small amount of suspended sediment is deposited on floodplains and helps to build streambanks.

Large Woody Debris

Large woody debris (LWD) exerts an important influence on channel morphology, sediment transport, and aquatic habitats in NFCC. LWD enters the channel mostly through windthrow and bank erosion at an average rate of 12 $m^3ha^{-1}yr^{-1}$, which is roughly equivalent to two logs 4 m long and 0.3 m in diameter entering a 100-m long reach each year (O'Connor and Ziemer 1989; Surfleet and Ziemer 1996; Elizabeth Keppeler, unpublished report, 1996). Approximately 340 m^3ha^{-1} of LWD was stored in or over the channel in 1987. This value is at the low end of the range for channels in old-growth redwood forests in Redwood National Park [average, 1,590 m^3ha^{-1}; range, 240-4,500 m^3ha^{-1} (Keller and others 1995)].

Sediment transport and storage is strongly affected by LWD. The formation of debris jams commonly causes bank erosion, but also induces sediment deposition upstream and downstream. As a result, there is no net effect on sediment yield downstream from additions of LWD (Napolitano 1996). Nevertheless, the release and capture of bed material by LWD probably induces strong temporal and spatial variation in bed load transport (Lisle 1989, Mosley 1981). We suspect that the variable storage capacity created by LWD may buffer inputs of bed material, making it difficult to detect short-term trends in sediment yield from the watershed.

Large woody debris is responsible for much of the channel complexity in NFCC. For example, 55 percent of the pools in a 370-m study reach just upstream of the NFCC weir were associated with LWD from 1991 to 1997. LWD provides cover for aquatic fauna and a food base for the aquatic ecosystem. Debris jams commonly lead to channel widening, bar deposition, and formation of multiple channels. In the course of the formation and breakup of a large jam, an active floodplain can be created within the widened area well below the elevation of the laterally eroded terrace. A floodplain can be expected to be more closely linked than higher surfaces to the aquatic ecosystem by storing and exchanging fine sediment, organic matter, and nutrients more frequently, and by offering new riparian habitats.

Response of the Channel to Recent Logging

The most profound effects of logging on NFCC persist from the legacy of 19th century logging (Napolitano, these proceedings). These include a relatively simple channel isolated by incision from its former floodplain (the present 1- to 2-m terrace) and the low volume and small size of LWD. Recent experimental logging has caused greater summer discharge (Keppeler, these proceedings), substantial inputs of LWD from blowdowns (Reid and Hilton, these proceedings), and modest increases in runoff during low-magnitude stormflows (Ziemer, these proceedings) and suspended sediment transport (Lewis, these proceedings). In this section, we attempt to relate these effects to changes in the mainstem channel, and discuss their effect on the aquatic ecosystem.

Bed Load Transport

First, we examine possible changes in the yield of bed load (ranging in particle size from fine sand to gravel) from the NFCC basin. Bed load yield since 1963 is evaluated by annual measurements of the volume of sediment filling the reservoirs behind the weirs in NFCC and South Fork of Caspar Creek (SFCC), although approximately 40 percent of the material trapped by the weirs is suspended sediment (Lewis, these proceedings). Annual yields in NFCC have varied from 0 (for seven of the 35 years) to 2,500 Mg (in 1974).

The magnitude and frequency of flows capable of transporting sediment and scouring or filling the channel each year must be accounted for in order to explore responses due to logging. To do this, we quantified the relative effectiveness of annual runoff to transport bed material. First, we computed an empirical relation between instantaneous bed load transport rate at Station ARF and discharge (data furnished by Jack Lewis). Then we applied this relation to values of mean daily discharge at the weir to estimate daily bed load yield and summed these values over each year to predict annual bed load yield for the entire period of record. This method underestimates the annual yield measured by reservoir surveys for a variety of reasons. However, we do not intend to predict reservoir filling by this method. Instead, we wish to weight daily discharges according to their sediment-transport capacity and thereby evaluate a "total annual effective discharge" (Q_e) in order to see if logging increased bed load transport independently of variations in runoff.

This response could appear as a departure from the relation between annual bed load yield (G_B) and Q_e (*fig. 2*) or a change in relative yields of NFCC and SFCC (not shown). No such response was evident. For corresponding ranges of Q_e, values of G_B for water years (WY) of the postlogging period (1990-1996) plot among the values of the prelogging period, and there was no apparent change in relative yields of NFCC and SFCC. A positive correlation between G_B and Q_e (r^2 = 0.58) indicates that bed load yield is dependent on storm runoff, thus the modest increase in storm runoff (Ziemer, these proceedings) may have increased bed load transport, but this was not borne out in bed load yields measured in the NFCC reservoir.

Large Woody Debris

In 1995, extensive tree blowdowns that were exacerbated in buffer strips along NFCC substantially increased LWD volumes in the channel and valley floor (Reid and Hilton, these proceedings). The volume of LWD in debris jams and pools increased significantly in NFCC compared to SFCC from 1994 to 1996, and a much greater volume lay suspended over the channel (Elizabeth Keppeler, unpublished report, 1996). According to Keppeler, "Straight open reaches are becoming stair-stepped with woody debris accumulations and stored sediment. In the last year alone (1996), the number of sediment storage features associated with woody debris has nearly doubled (unpublished step data). On the SFCC, no evidence of a similar trend is observed."

Scour and Fill of the Channel

Channel changes in 2.4 km of the mainstem have been monitored since 1980 by annual (or less frequent) surveys of 60 channel cross sections spaced at an average of 40 m between Station ARF and the old splash dam (Preface, fig. 2, these proceedings). Net scour and fill measures the accumulation or depletion of sediment in the channel; it is the net change in cross-sectional area of the channel (i.e., fill minus scour). Total scour and fill measures channel variability; it is the cross-sectional area undergoing change (i.e., scour plus fill).

Mean annual total scour and fill for the whole channel correlated strongly with Q_e (*fig. 2;* r^2 = 0.90). This suggests that any increase in bed load yield from augmented magnitudes of low-to-moderate peak flows after logging (Ziemer, these proceedings) could come from the bed and banks of the main channel.

We examined spatial patterns of erosion and deposition in the main channel by calculating values of net and mean annual total scour and fill at each cross section for a prelogging period (1986-1990) and a postlogging period (1991-1997). Both measures of scour and fill varied widely during both periods but were greater during the postlogging period (*fig. 3*). The entire channel filled an average of 0.08 m^2 during the prelogging period and 0.24 m^2 during the postlogging period. This is equivalent to about 1,040 Mg of bed material filling the channel during the postlogging period, or about 60 percent of the bed load yield for that period. Therefore, a substantial portion of bed load has accumulated in the channel.

Mean annual total scour and fill generally increased downstream and was commonly high near tributary junctions, although no difference was apparent between logged and unlogged tributaries. Net fill was highest in the downstream 700 m of channel, which is adjacent to a clearcut buffer strip along the left bank. Most

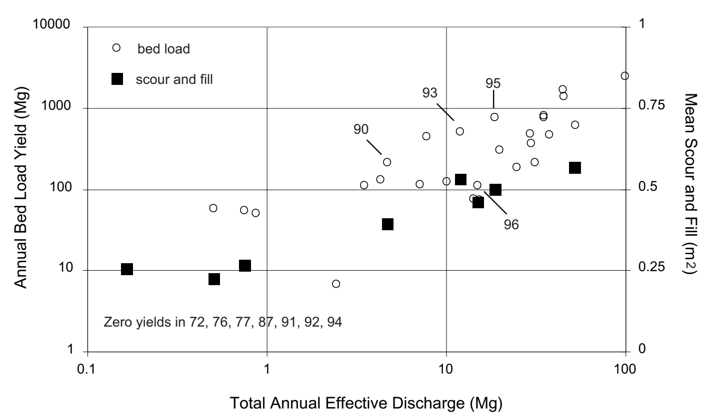

Figure 2—Annual bed load yield measured in the North Fork reservoir and mean annual total scour and fill versus total annual effective discharge. Data points are identified by year for the postlogging period.

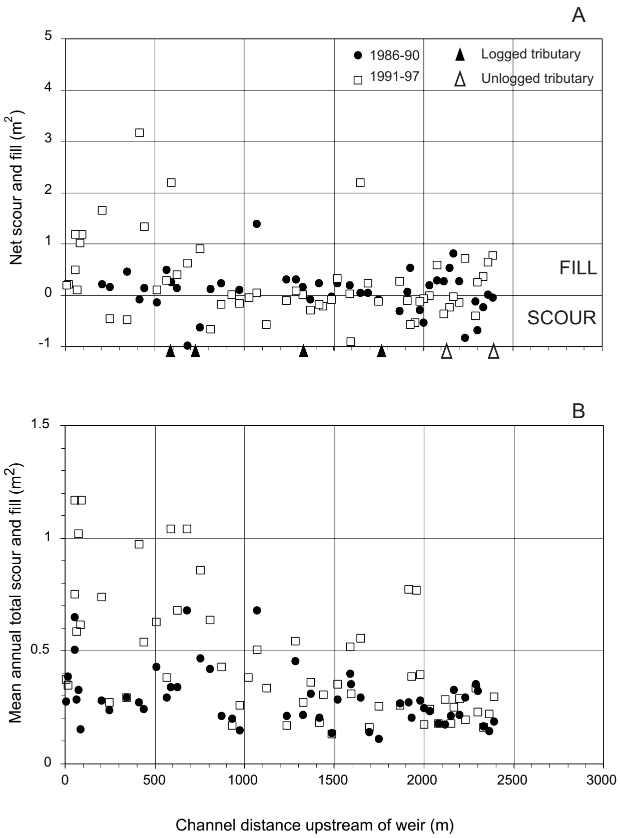

Figure 3—Net and average annual scour and fill versus channel distance upstream of the North Fork weir for the prelogging (1986-1990) and postlogging (1990-1997) periods. Values are determined from repeated surveys of channel cross sections. Values of net scour and fill are missing for channel distances of 0 to 200 m (1986-1990) because of missing measurements at the beginning of the period.

of the filling during the postlogging period occurred here in WY1996, shortly after windstorms blew down trees in buffer strips (Reid and Hilton, these proceedings). This association of high net fill in time and place with LWD inputs substantiates Keppeler's account of channel changes associated with new LWD. We have monitored pool dimensions in part of this reach since 1991.

Pools

We measured residual volume and fine-sediment volume (Hilton and Lisle 1993) in all pools upstream of the main weirs in NFCC (a 340-m long reach) and SFCC (a 470-m long reach) annually during the postlogging period (1991 to 1997). Scoured pool volume (SPV) is residual pool volume plus fine sediment volume; it measures the basin scoured in bed material without the more transient fine sediment that is deposited during waning flows of flood hydrographs. Total SPV nearly tripled in NFCC and varied non-systematically in SFCC during the period (*fig. 4*). In NFCC, the fraction of residual pool volume filled with fine sediment (V*; Lisle and Hilton 1992) increased from 1991 to 1994 and then decreased below the initial value by 1997. In SFCC, V* decreased in the same period, except for a slight rise in 1997.

Discussion and Conclusions

Logging increased low and moderate streamflows and greatly increased the input of LWD from blowdowns in buffer strips bordering the mainstem channel. Apparent channel responses, particularly in a downstream reach affected by blowdowns, have been an increase in storage of bed material, an increase in the number and total volume of pools, and a temporary increase in fine sediment stored in the channel. What is the most likely explanation of these responses?

An increase in peak flows would supply more energy to scour pools, but if accompanied by increased erosion, could cause net sedimentation of pools. This may have been expressed by a greater accumulation of fine sediment as pools enlarged in NFCC (increased V* and SPV). However, a net accumulation of sediment in the same reach where pools enlarged runs counter to an argument that increased runoff alone has scoured sediment from pools. Moreover, we believe that increases in storm runoff were too modest to significantly affect sediment transport or pool volume.

Simultaneous channel fill and the enlargement and proliferation of pools without a change in bed load yield can be explained by the effects of increased LWD. Increased LWD volumes tend to increase the number and volume of pools by creating more stepped and converging flow patterns (Keller and Swanson 1979). Newly formed debris jams can also trap bed load and promote scour downstream by

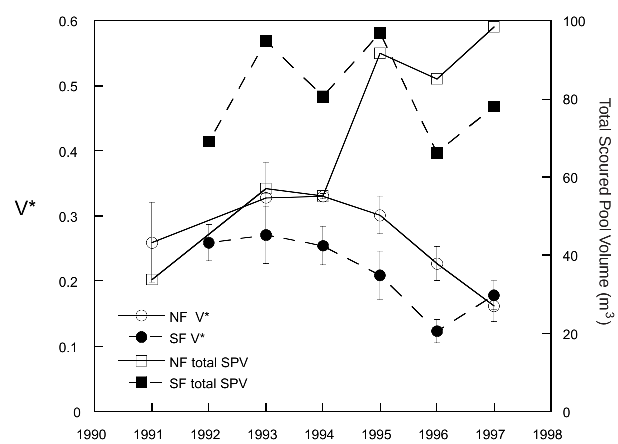

Figure 4—Temporal variations in fraction of residual pool volume filled with fine sediment (V*) and total scoured pool volume (SPV) in downstream reaches of North Fork (NF) and South Fork (SF) Caspar Creek. Brackets around V* values denote ± 1 s.e. WY1992 was exceptionally dry, so we assume there was no change between existing or missing values for WY1991 and WY1992.

locally and temporarily starving the channel of sediment. LWD also increases sediment storage by trapping sediment behind debris jams and by extracting flow energy elsewhere that would otherwise be exerted on the channel bed. New LWD also increases bank erosion, but the net result for sediment transport in NFCC was neutral before recent logging (Napolitano 1996), and no changes were detected in bed load yield in NFCC after logging.

Our interpretation is consistent with results from an experiment on similar channels in southeastern Alaska, where LWD was removed from logged channels that had accumulated large volumes from logging slash (Lisle 1989), and from an experiment on channels in the blast zone near Mt. St. Helens, Washington, where large volumes of sediment and LWD were introduced by the eruption and LWD was experimentally removed (Lisle 1995). In both cases, which represent a reversal of the effects observed in NFCC, removal of LWD caused a loss of both pool volume and stored sediment. In summary, increased LWD is commonly associated with increased sediment storage and pool volume in a variety of gravel bed streams.

Recent changes in NFCC favor aquatic vertebrates. Increases in populations of older juvenile steelhead trout and salamanders (Nakamoto, these proceedings) may have resulted from increased LWD (as cover), pool volume, and habitat complexity. Moreover, coho salmon, which have a tenuous presence in NFCC and SFCC because of the small size of these streams, are especially favored by large volumes of LWD and pool habitat (Nickelson and others 1992). Productivity is probably also augmented by greater summer flows.

However, an interpretation that logging and, in particular, consequent increases in LWD from blowdown are favorable for the aquatic ecosystem may be a misconception created by the short time over which we have observed effects. To look beyond the immediate results, we must consider the long-term supply of LWD, which was severely depleted by 19th-century logging, further depleted by recent logging of second-growth trees that could have entered the channel, and cashed in by recent blowdown of some trees in the streamside buffer zone. The prognosis for future decades is a greater departure from natural volumes of LWD in the channel as existing LWD decays and inputs decrease from depleted riparian sources. We predict that reaches bordered by clearcuts and buffer strips will lose sediment storage, pool volume, and habitat complexity as inputs of LWD decline.

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