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EFFECT OF BASELEVEL CHANGE ON FLOODPLAIN AND FAN SEDIMENT STORAGE AND EPHEMERAL TRIBUTARY CHANNEL MORPHOLOGY, NAVARRO RIVER, CALIFORNIA

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ABSTRACT

Managed baselevel lowering in tributaries that emerge from small canyons onto forested floodplains affects floodplain and fan sediment storage and small ephemeral tributary channel morphology in the Navarro River basin, Mendocino Country, California, USA. Numerous small tributaries (drainage areas up to several square kilometres) flow through culverts under Highway 128 across the forested floodplain of the Navarro River and one of its major tributaries, the North Fork. Excavation significantly deepened and widened these small tributaries upstream and downstream of culverts under the highway following the 1997 flood (recurrence interval 12 years), that inundated both the floodplain and the highway and culvert system. The excavation lowered the local baselevel of the tributary systems within the floodplain. This field study documents the effect of the lowered baselevel on floodplain and fan sediment storage and ephemeral tributary channel morphology. Excavation created defined channels in the floodplain where no channels previously existed. Additionally, the excavation and baselevel change created steps, or knickpoints, that migrated headward and incised the upstream tributary channels. Tributary incision decreases the sediment storage potential of the fan and floodplain and reduces the residence time for storage of fine sediment. A reduction in fine sediment residence time degrades downstream habitat for anadromous fish and other aquatic organisms in the Navarro River. Large wood influences floodplain and small tributary channel morphology by forming steps and increases sediment residence time by trapping sediment in forested tributary–fan–floodplain systems. Although this field investigation is specific to the Navarro River basin, our findings linking culvert maintenance excavation to geomorphic processes may be extended to other roads on forested floodplains in the Pacific Northwest or other systems with roads on floodplains. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: baselevel; floodplain; fan; sediment storage; residence time; highway

INTRODUCTION

The Navarro River in Mendocino County, California, enters the Pacific Ocean 32 km south of the town of Mendocino (Figure 1). Steep tributary canyons and hillslopes typical of northwest California result in high natural erosion rates. Land uses in the basin such as logging, agriculture, rural residential development, grazing, and water diversions have accelerated historic erosion rates and have degraded habitat for anadromous fish such as coho salmon and steelhead trout (Florsheim *et al.*, 1998; Division of Water Rights, 1998; Entrix *et al.*, 1998).

While numerous studies document the link between roads, increased flow and sediment production related to slides, gullies, road surface erosion and culvert failure in steep and forested areas (Reid and Dunne, 1984; Hagans and Weaver, 1987; Montgomery, 1994; Best *et al.*, 1995; Weaver *et al.*, 1995; Wemple *et al.*, 1996; Furniss *et al.*, 1999), there have been no studies specifically documenting the link between culvert maintenance excavation and geomorphic processes on forested floodplains. This study investigates the effect of local baselevel lowering caused by highway culvert maintenance on floodplain and fan sediment storage

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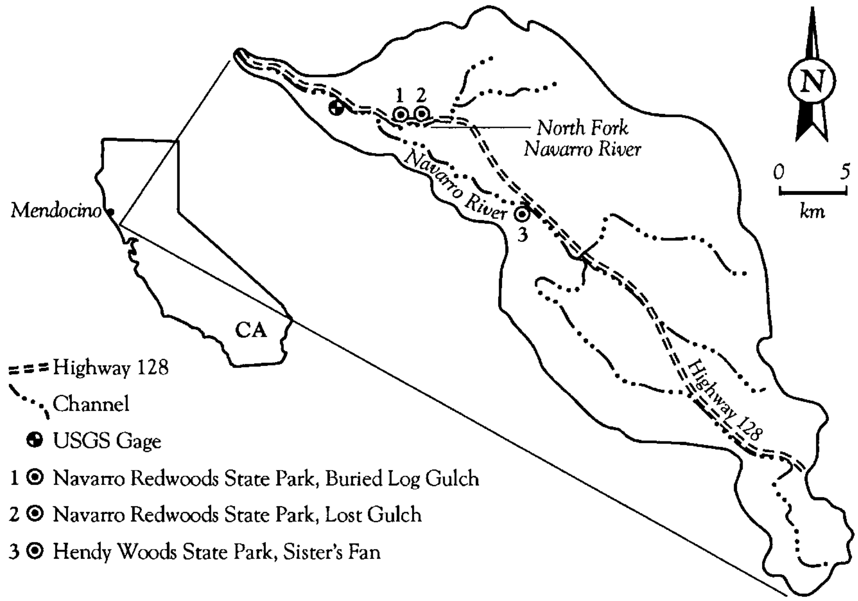

Figure 1. Location of Navarro River basin, California, its main tributaries, the three study sites, and the USGS gauging station. Relief in the basin ranges from sea level at the mouth to 11 190 m at the basin divide

and ephemeral tributary channel morphology in the Navarro River basin. Baselevel is the elevation to which a fluvial system can erode (Schumm, 1993). In this paper, we define a 'managed baselevel' change as the baselevel lowering due to highway culvert maintenance activities. We describe the effects of the managed baselevel lowering on sediment storage and residence time and discuss the potential effects on physical habitat in the downstream fluvial system.

Floodplain fans store sediment deposited on floodplains at the mouth of small ephemeral tributary canyons, and provide a buffer between hillslope sediment sources and main channel aquatic habitat. Field data for this investigation, collected from three tributary–fan–floodplain systems in the Navarro River basin, provide a comparison of the morphology and response of two study sites on the North Fork Navarro River that are influenced by State Highway 128 to one site on the main stem Navarro River that is not affected by the highway. The comparison provides insight to the effects of a managed baselevel change on geomorphic processes such as: (1) headward incision upstream of the excavation; and (2) the creation of a defined channel in portions of the floodplain that would not otherwise contain channels.

This study reports data for three ephemeral tributary systems in the Navarro basin; however, field reconnaissance suggests that maintenance of numerous small tributary crossings induces similar responses elsewhere on the North Fork and Navarro River floodplains. Results of this work provide data that constitute an element of the overall sediment budget of the Navarro basin. These findings may aid in development of highway management practices that minimize geomorphic impacts to floodplain and channel morphology and aquatic habitat in the Navarro and other watersheds throughout the Pacific Northwest or other systems where roads on floodplains cross small tributary drainages.

Conceptual model of effect of managed baselevel change on tributary–fan–floodplain sediment residence time

In order to illustrate the tributary–fan–floodplain system, we present a conceptual model describing the effect of managed baselevel change due to culvert maintenance excavation on headcutting and sediment residence time in the tributary–fan–floodplain systems (Figure 2). In a natural tributary–fan–floodplain

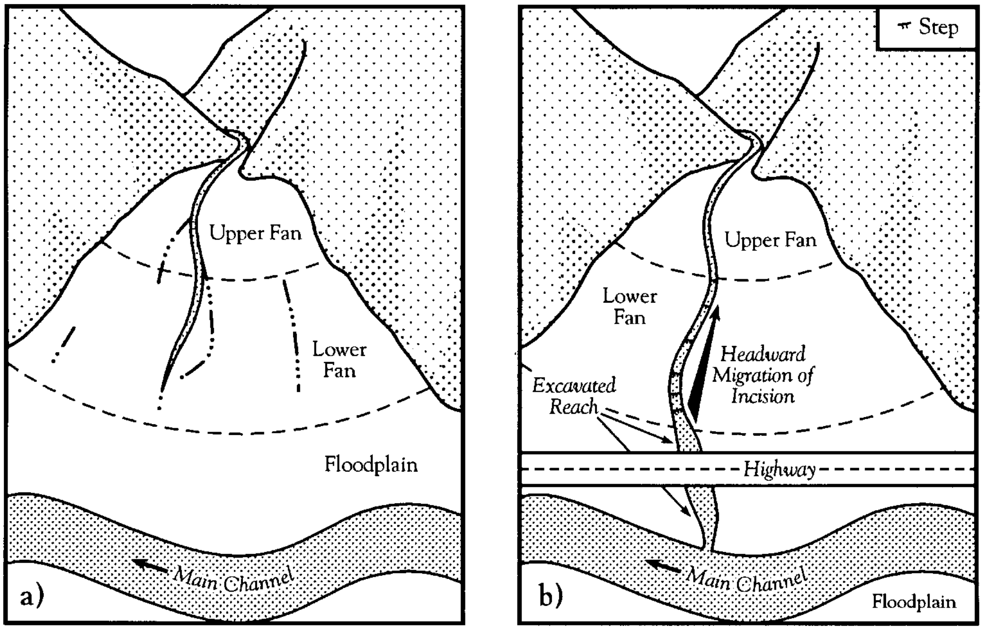

Figure 2. Conceptual model illustrating the effect of headcutting on sediment residence time in the tributary–fan–floodplain systems: (a) a natural tributary–fan–floodplain system; (b) a tributary–fan–floodplain system that is crossed by a highway

system, flow emerges from a canyon and flows through the upper fan in a defined channel (Figure 2a). The flow splits into distributary channels, and then as channels disappear at the distal margin of the lower fan, flow infiltrates into the fan and floodplain sediment and continues toward the main channel as groundwater. In this case, the fan and floodplain sediment storage function is intact and the floodplain fan buffers the input of sediment from the tributary. In contrast, a tributary–fan–floodplain system that is crossed by a road is influenced by culvert maintenance excavation that lowers the baselevel of the system to a new lower elevation (Figure 2b). In this case, the headward migration of the step and incision lowers the tributary bed elevation upstream of the excavated reach. Maintenance excavation downstream of the road connects the main channel to the incised tributary upstream, bypassing the sediment storage potential and reducing the residence time of sediment in the fan and floodplain system.

STUDY AREA AND METHODS

The Navarro River drains 785 km^2 in the Coast Ranges in Mendocino County, California (Figure 1). Precipitation in the basin is highly seasonal, falling primarily between October and April, typical of the wet Mediterranean-type climate of north coastal California (Muhs *et al.*, 1987). Large storms, floods and sediment transport processes are episodic. The North Fork Navarro River (drainage area 190 km^2) is the most downstream tributary of significant size to join the Navarro River.

State Highway 128 follows the narrow forested floodplain along the lower gradient portion of the Navarro River and the North Fork. The highway is raised up to 1 m on fill above the elevation of the surrounding floodplain and crosses numerous small ephemeral tributaries that flow nearly perpendicular to the road. All floodplain flow is concentrated towards culverts that convey water under the highway and periodic tributary excavation is required to maintain the culverts free of sediment and to facilitate floodplain drainage. The most recent excavations occurred following the winter of 1997 in all of the tributary channels immediately upstream and downstream of the culverts when tributaries were both deepened and widened as part of highway maintenance operations along the North Fork and lower Navarro River (Renee Pasquinelli,

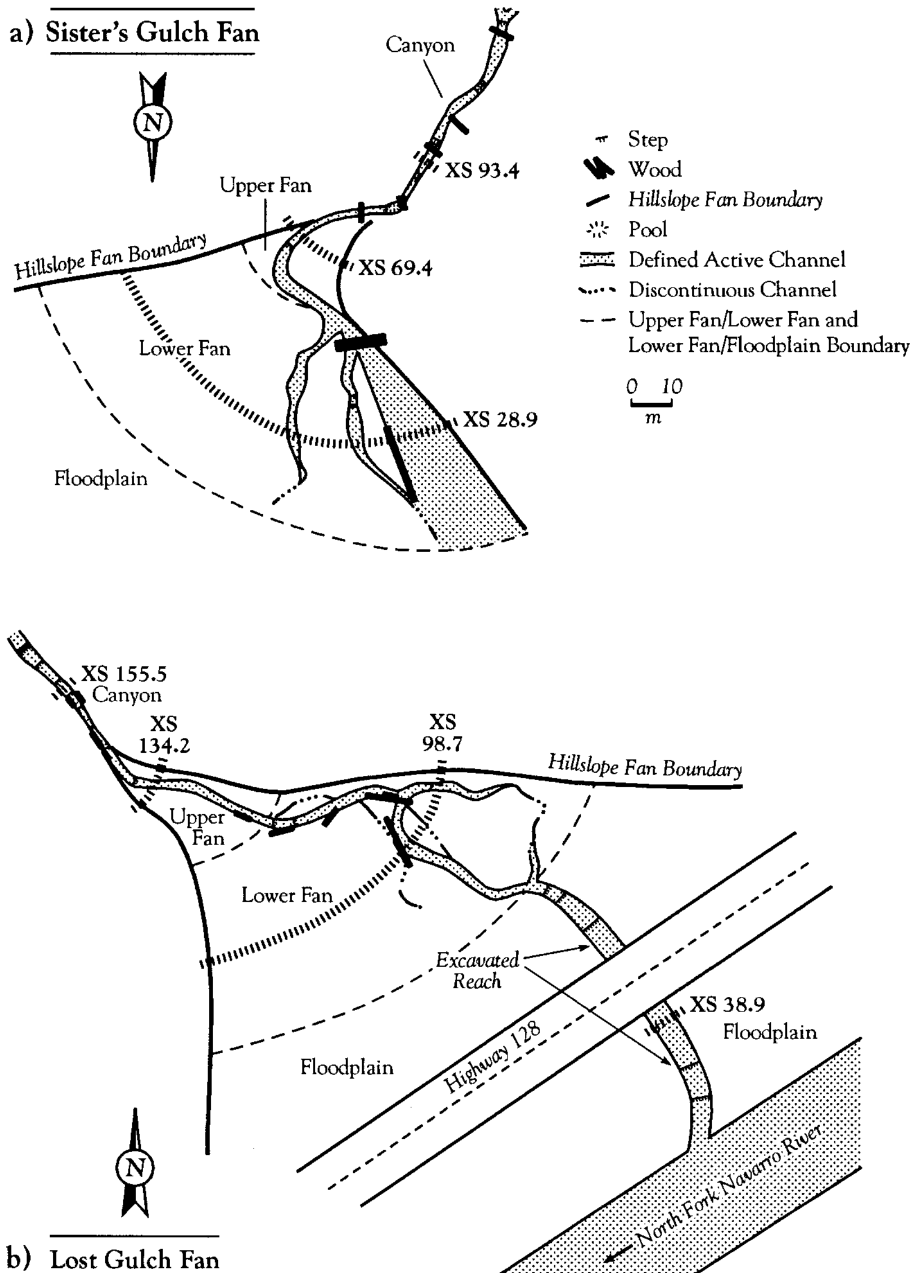

Figure 3. Maps of study sites constructed using a tape and compass were prepared in the field at a scale of 1 inch = 5 m; (a) Sisters' Gulch, Hendy Woods State Park; (b) Lost Gulch MP 9·94, Navarro Redwoods State Park; (c) Buried Log Gulch MP 8·86, Navarro Redwoods State Park. Tributaries exit canyons, and split into distributary channels on fans. Excavated channels up and downstream of Highway 128 concentrate flow and sediment in a defined channel that flows to the North Fork

California State Parks, personal communication, 1998). The January 1997 flood had a recurrence interval of about 12 years at the USGS gauging station Navarro River near Navarro (number 11468000; see Figure 1). During the flood, flow inundated the floodplain and Highway 128, depositing both sediment and woody debris. Maintenance excavation following the 1997 flood lowered the tributary's thalwegs to the same

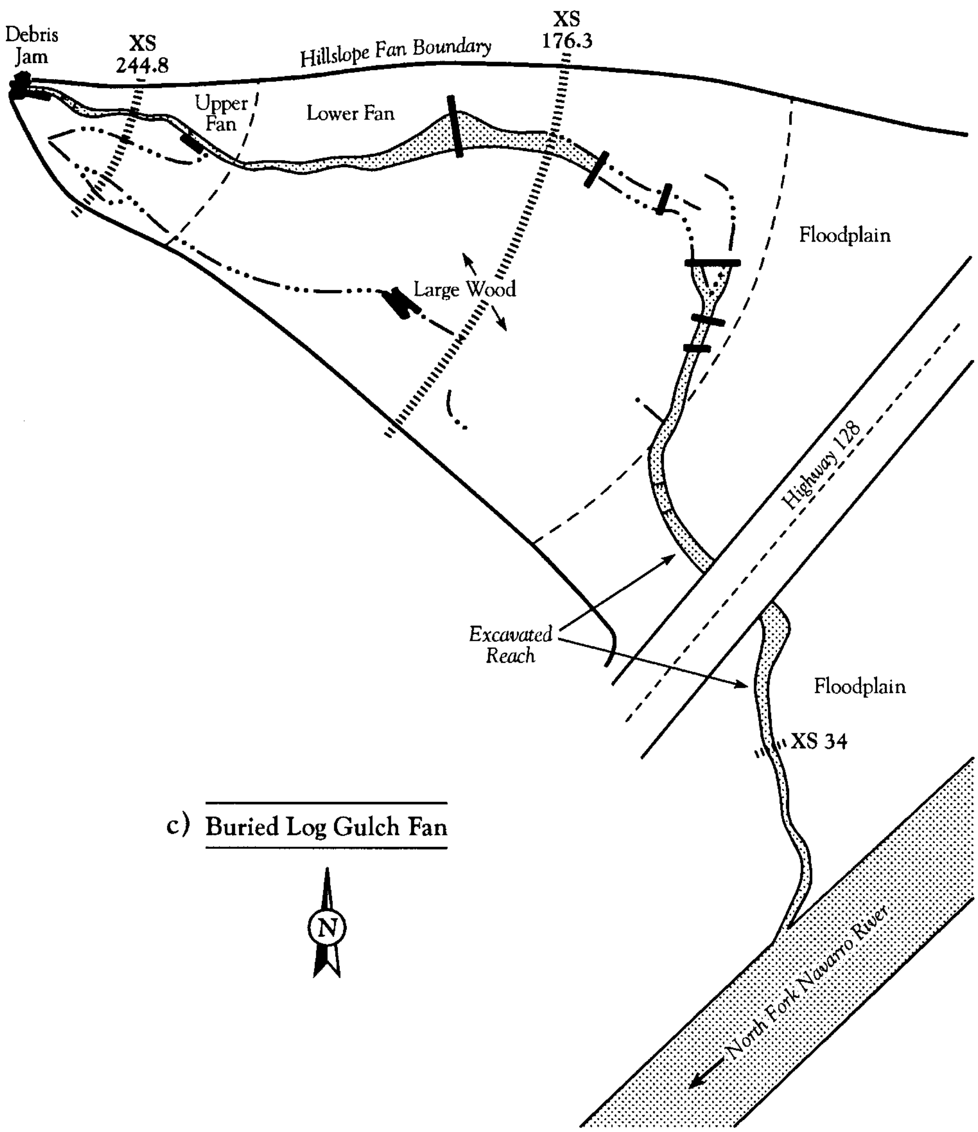

Figure 3. (c)

elevation as the base of the culverts, a few metres below the elevation of the surrounding floodplain surface. Sediment excavated from these tributaries was placed adjacent to their channels on the floodplain of the North Fork Navarro River.

Study sites

Three forested floodplain study sites (Figure 1) were selected for detailed investigation in order to compare the geomorphic conditions on tributary–fan–floodplain systems with and without the influence of Highway 128 (Florsheim *et al.*, 1998). The study site selected in Hendy Woods State Park on the southwestern side of the main stem of the Navarro River in the lower Anderson Valley is not affected by Highway 128. In contrast, the two sites in Navarro Redwoods State Park on the northeastern side of the North Fork are influenced by the highway and the managed baselevel lowering resulting from highway culvert maintenance activities.

At Hendy Woods State Park, an old-growth forest dominates the floodplain and fan system. We call an unnamed tributary that flows northeast from Greenwood Ridge to the Navarro River 'Sisters' Gulch' (drainage area 0·6 km^2). Sisters' Gulch has incised a narrow canyon through Franciscan sandstone and shale and Quaternary river terrace deposits. The site is one of several small tributaries draining Greenwood Ridge that create small fans where the canyons meet the forested floodplain of the Navarro River.

At Navarro Redwoods State Park, State Highway 128 crosses several tributary–fan–floodplain systems. This narrow floodplain was logged as early as 1860, and the existing second and third growth forest is 50 to 150 years old. The two study sites crossed by Highway 128 are similar to numerous other small tributaries that flow southward from Navarro Ridge toward the North Fork which have incised canyons into Franciscan assemblage sandstone and shale. In this study, we call the unnamed tributary at State Highway Mile Post (MP) 9·94 'Lost Gulch' (drainage area 0·3 km^2), and we call the tributary at MP 8·86 'Buried Log Gulch' (drainage areas 0·5 km^2).

Method to calculate sediment production

The total volumetric sediment production rate (q_t) resulting from maintenance practices, where tributaries cross the floodplain and flow through culverts under the highway, may be quantified as the sum of tributary sediment erosion rates due to: (1) headcutting upstream of the excavation (q_h); and (2) erosion of excavated material placed on the floodplain adjacent to the tributary's excavated channel (q_e). The sediment production rate from headward incision resulting from culvert maintenance excavation from all of the tributaries that are crossed by Highway 128 is:

$$q_h = 1/\Delta t \sum_{i=1}^{n} (V_h)_i \tag{1}$$

where n is the number of tributaries, Δt is the time interval (taken as one year in the present study), and $(V_h)_i$ is the volume of sediment produced due to headcutting at an individual tributary. The sediment production rate due to scour of material placed on the floodplain adjacent to each tributary channel excavated upstream and downstream of the highway is:

$$q_e = 1/\Delta t \sum_{i=1}^{n} (V_e)_i \tag{2}$$

where $(V_e)_i$ is the volume of sediment produced due to scour of excavated material at each tributary. The sum of these rates provides an estimate of the total volumetric sediment production rate from highway culvert maintenance practices:

$$q_t = q_h + q_e = 1/\Delta t \sum_{i=1}^{n} (V_h + V_e)_i \tag{3}$$

where lateral sediment input due to bank erosion associated with headcutting is neglected. The actual sediment production rate would be highly variable from year to year due to the episodic sediment erosion and transport processes in the Navarro basin. The total volumetric sediment production rate resulting from maintenance practices at floodplain culverts may be small relative to the total sediment budget of the Navarro basin. However, these practices release silt and increase the rate of fine sediment contributed to main channel aquatic habitat. Silt that would have been stored for longer periods of time in off-channel storage sites may

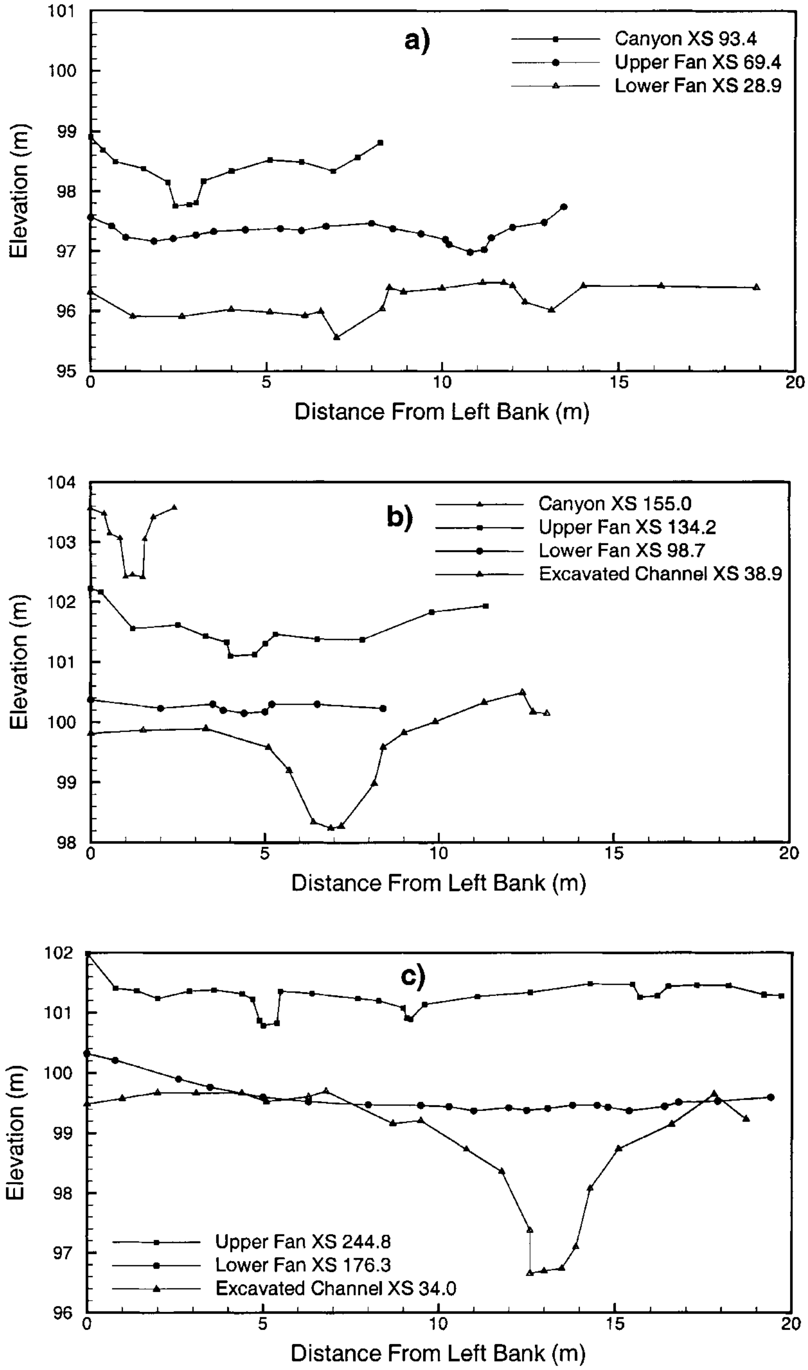

Figure 4. Cross-sections at study sites surveyed using an automatic level: (a) Sisters' Gulch, Hendy Woods State Park; (b) Lost Gulch MP 9·94, Navarro Redwoods State Park; (c) Buried Log Gulch MP 8·86, Navarro Redwoods State Park, showing narrow channel in canyon and upper fan, relatively shallow wide channel across lower fan, and an enlarged deep and wide excavated channel downstream of Highway 128 in the portion of the floodplain that would not normally contain channels

Table I. Comparison of primary step height due to headward incision to other steps

Study site	Primary step height (m)	Average step height: Canyon (m)	Canyon n†	Floodplain–Fan* (m)	Floodplain–Fan* n†
Sisters' Gulch	NA	0·23	3	0·29	7
Lost Gulch	0·62	0·47	8	0·15	9
Buried Log Gulch	0·40	0·90	2	0·17	15

* Excluding primary step
† Number of steps

have deleterious effects on already degraded aquatic habitat. Our field investigation quantifies q_t for two floodplain fan systems in the North Fork basin over a one year period.

RESULTS AND ANALYSIS

Morphology of tributary–fan–floodplain systems

The morphology of the Sisters' tributary–fan–floodplain system on the main Navarro River at Hendy Woods State Park is not affected by Highway 128 (Figure 3a). The tributary emerges from the canyon and forms a fan on the floodplain where sediment transported in both fluvial and debris flows is deposited. The main tributary and secondary and abandoned distributary channels disappear where the lower fan and the floodplain merge. Cross-sections surveyed across the tributary in the canyon and upper fan show a single channel, while the cross-section surveyed across the lower fan illustrates two distributary channels (Figure 4a). There is no continuous defined channel across the floodplain that connects the tributary to the main channel of the Navarro River. In the canyon, tributary morphology consists of step–pool sequences, where steps form over redwood roots, fallen branches and logs, boulders or irregularities in bedrock. Average step height (measured from the base of the plunge pool to the top edge of the step) on the fan and in the canyon, formed where redwood roots or debris cross the channel, are presented in Table I.

The two study sites in Navarro Redwoods State Park crossed by State Highway 128 – Lost Gulch and Buried Log Gulch – were selected to illustrate tributary–fan–floodplain systems where geomorphic processes are affected by the highway. The tributary and fan morphology at both sites is similar to the natural Sisters' system in the canyon and upper fan reaches; however, the lower fan and floodplain reaches differ in the following way. Excavation of the tributary upstream and downstream of culverts under Highway 128 has lowered the local baselevel to the elevation of the base of the culverts. The extent of excavation was identified by noting the presence of heavy equipment (Bobcat™) shovel marks in the silty floodplain sediment. The excavation created a deepened and widened channel and initiated formation of a step and upstream headcutting, resulting in a defined channel that connects the tributary to the North Fork Navarro River. Geomorphic maps of Lost Gulch and Buried Log Gulch show that these tributaries are extended by excavation across the floodplain and connected to the North Fork (Figure 3b and c), in contrast to the Sisters' system where the tributary terminates near the boundary between the lower fan and floodplain. Cross-sections of the narrow tributaries in the canyons and in upper fan reaches at Lost Gulch and at Buried Log Gulch show that the tributaries are shallower in the lower fan and significantly deeper and wider in the excavated floodplain reaches (Figure 4b and c), again in contrast to the undisturbed Sisters' system, where there is no defined channel in the floodplain.

At both study sites affected by the highway, incision extends upstream from the excavated reach and forms one or more knickpoints, or steps. The morphology of the excavated reaches is characterized by a primary step that migrates upstream of the excavation (Table II). At Lost Gulch, in addition to the primary step, the

Table II. Morphology of the excavated reaches

Study site	Culvert width × height (m)	Upstream excavation Width (m)	Depth, d* (m)	Length (m)	Primary step character Step height, H (m)	Step H/d† (m/m)	Downstream excavation Width (m)	Depth* (m)	Length (m)
Lost Gulch	1·2 × 0·6	3·3	1·6	5·7	0·6	0·6	4·1	2·1	23·9
Buried Log Gulch	0·9 × 0·6	3·5	1·2	16·4	0·4	0·5	3·3	2·1	68·3

* Depth from edge of floodplain to thalweg measured from floodplain surface beyond excavation debris placed adjacent to tributary channel
† H/d is ratio of step height, H, from base of plunge pool to top of step in the upstream excavation, and d is depth from edge of floodplain to top of step

tributary has formed a series of steps upstream of the excavation, and incision extends upstream to the lower fan. At Buried Log Gulch, the primary step is headcutting into the abandoned logging road where the road material consists of gravel, fine sand and silt. At Lost Gulch, 35 per cent of the change in elevation associated with steps on the floodplain fan is accounted for by the primary step, which is about four times the average step height. At Buried Log Gulch 15 per cent is accounted for by the primary step, which is about 2·4 times the average step height. Data comparing primary step height due to headward incision to other steps, mostly related to woody debris, are reported in Table I.

Fallen redwood logs, branches and stumps, as well as large-diameter living redwood trees, affect sediment storage on the fan and floodplain at the study sites primarily by stabilizing steps in the tributary and distributary channels on the fan and by acting as dams that store sediment. The abundance of recently fallen trees and large branches lying perpendicular to the tributary and across other portions of the fan at Buried Log Gulch may stabilize the grade and reduce the future rate of headward incision.

Sediment production due to baselevel change and culvert maintenance excavation

The magnitude and duration of sediment-transporting flow in the ephemeral tributaries influences the rate of headward migration of incision. During the winter of 1998–1999, the duration of flow in the ungauged ephemeral tributaries was approximately five months. After May 1999, we observed that the surface component of flow did not extend beyond the upper fan portion of the tributary–fan–floodplain systems as water from the tributaries infiltrated into the fan–floodplain sediment. In the later part of the wet season, flow was discontinuous, flowing in pools and deeper portions of the tributary, and disappearing under alluvium in the shallower parts of the channel and distal portions of the fans.

At Lost Gulch (Figure 5a), there was no migration of the step, probably because the duration of flow was not long enough to significantly erode the fine-grained unconsolidated floodplain sediment, thus $V_h = 0$. However, the local steepening of the bed slope associated with the recent excavation did lead to deepening of the plunge pool downstream of the step by about 0·1 m during the five month period. As noted by Leopold *et al.* (1964), the formation of a plunge pool downstream of a step can contribute both to erosion at the base of the step and to downstream removal of the eroded sediment, both of which are prerequisites for headcutting.

At Buried Log Gulch, the step migrated upstream about 1·5 m (Figure 5b). The apparent retreat rate, given as $\Delta x/\Delta t$, where Δx is migration distance and Δt is a one year time period, is 1·5 m a^{-1}. This corresponds to a volumetric sediment production rate, $V_h/\Delta t$ due to the headward migration of the step of 0·9 m^3 a^{-1} (where V_h is calculated as the product of step height (0·4 m), channel width at the step (1·5 m) and migration distance (1·5 m)). In addition to the headcutting, there was a deepening of the plunge pool by about 0·1 m, similar to the amount at Lost Gulch. Deposition of sediment immediately downstream of the plunge pool aggraded the

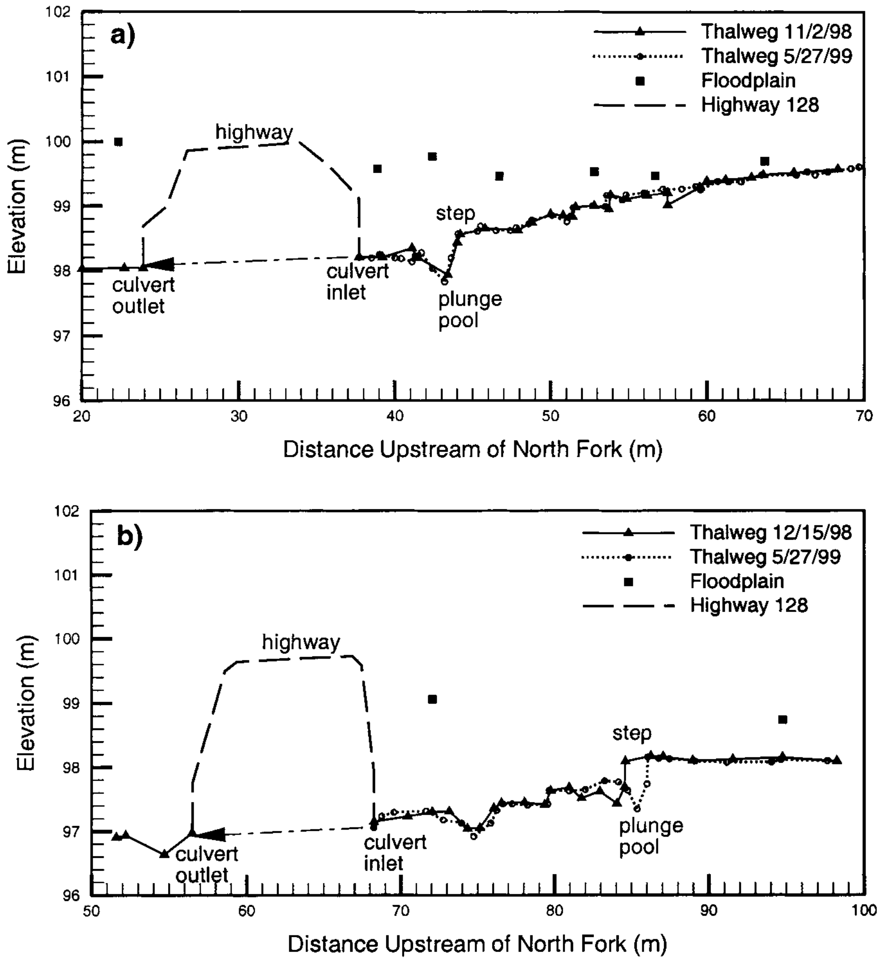

Figure 5. Longitudinal profiles surveyed in autumn 1998 and spring 1999 showing step resulting from highway maintenance excavation at: (a) Lost Gulch MP 9·94; (b) headward incision at Buried Log Gulch MP8·68

channel in the location of the former plunge pool up to about 0·2 m. Another step upstream of the culvert was stabilized by the presence of wood in the channel and did not move.

At Lost Gulch, V_e, the approximate volume of material excavated upstream and downstream of Highway 128, is about 235 m^3, and is about 540 m^3 at Buried Log Gulch. This volume of sediment, primarily composed of silt, was placed on the floodplain adjacent to each tributary channel where it may be reworked by future overbank floods from the North Fork. However, the sediment production rate, $V_e/\Delta t$, was equal to zero at both sites during the winter of 1998/99, since there was no overbank flow from the North Fork. Using Equation 3 to quantify the total sediment production rate from the two study sites ($n = 2$) over the one year period of study yields $q_t = 0{\cdot}9$ m^3 a^{-1}. Because geomorphic processes in the Navarro basin are episodic, further investigation is warranted to quantify the effects of highway maintenance practices throughout the basin over longer time intervals.

DISCUSSION AND CONCLUSIONS

Highway maintenance excavation on the forested floodplain in the Navarro River basin creates a lower managed baselevel that initiates adjustment of the upstream longitudinal profile in ephemeral tributaries, and alters the sediment storage capability of the floodplain and floodplain fans. Results of this study documenting the role of culvert maintenance excavation along Highway 128 suggest that the lowering of the local baselevel to the elevation of the base of the culvert altered geomorphic processes and morphology in forested tributary–fan–floodplain systems in two significant ways: (1) the excavation initiates headward migration of incision that may transform a depositional system into an erosional system; and (2) the excavation alters channel morphology of the tributary by creating a relatively deep and wide defined channel in a portion of the floodplain that would not otherwise contain channels, providing rapid conveyance of flow and sediment from tributaries to the main channel. The management implications of these geomorphic effects are related to the reduction of tributary–fan–floodplain sedimentation storage volume and residence time and the potential impacts of increased fine sediment supply to downstream habitat.

Baselevel lowering and headward migration of incision

Culvert maintenance excavation is intended to keep the culvert entrances and exits free of sediment and woody debris and to speed drainage of the floodplain following floods. The local baselevel of each system crossed by Highway 128 is changed to a new elevation corresponding to the elevation of the base of the culvert. In effect, maintenance excavation creates a managed baselevel that could change if management practices changed, or if maintenance does not regularly remove accumulated sediment. For example, if periodic excavation ceased, the small tributary upstream of each culvert could fill in with sediment to the elevation of the surface of the floodplain (or even the road surface), assuming sufficient sediment supply. The configuration would then be similar to that at Sisters' Gulch, the likely natural state of the system, where the distal end of the fan surface merged with the North Fork floodplain sediment and water infiltrated into the sediment and flowed as groundwater towards the main channel. As long as periodic maintenance excavation is conducted to maintain the lower managed baselevel at the elevation of the base of the culvert, the geomorphic response of the upstream system is likely to be incision, despite the variability in sediment supply from upstream. For example, a debris flow from the tributary that deposits sediment on the fan could fill an incised channel and divert flow to a new course on the fan. However, flow will eventually be diverted towards existing culverts, and as long as periodic excavation to the elevation of the base of the culvert continues, headcutting and upstream incision are likely to follow.

The response of the system to the baselevel change depends on several factors including the rate, amount and direction of the baselevel change (Schumm, 1993) as well as on the erodibility of the floodplain and tributary source areas. The excavation at Lost Gulch and Buried Log Gulch created significant steps with an abrupt change in slope between the upstream channel and the excavated reach. In non-cohesive sediment such as in the North Fork floodplain–fan systems, these steps are likely to flatten as erosion migrates headward and lowers the entire profile equal to the amount of the initial lowering of the bed, as observed in other alluvial systems and flume studies (Leopold and Miller, 1956; Brush and Wolman, 1960; Pickup, 1975; Begin, 1978; Begin *et al.*, 1981). Over time, there will be a progressive reduction in slope upstream of the headcut, and the longitudinal profile of the tributary will change as sediment is eroded upstream of the step, where the velocity and shear stress are greatest, and deposited downstream of the step. The rate of longitudinal profile change on the fan and floodplain will depend on parameters such as the future sediment supply, transport rate, and the character of the upstream bed and bank material (Brush and Wolman, 1960; Begin, 1978; Begin *et al.*, 1981; Gardner, 1983) as well as on non-fluvial elements, such as large wood that may locally stabilize the bed. In the Navarro basin, where sediment supply and transport processes are episodic and highly variable, and where the fan–floodplain sediment deposits are not homogeneous, headcut migration is also likely to be episodic. The longitudinal profile evolution may also be variable, steepening and flattening in response both to the headward migration of incision and the sediment supply from upstream (Wolman, 1987). An increase in bed width and a reduction in the steepness of channel banks is likely as incision proceeds upstream in alluvial streams responding to baselevel lowering (Pickup, 1975, 1977). Further upstream, in the bedrock portion of the tributary, continued headcutting of incision will depend on the sediment supply, transport capacity, erodibility of the bedrock, grain size, and on excess shear stress needed to alter the longitudinal profile (Sklar and Dietrich, 1998).

Equation 3 provides a method to estimate the total sediment production from highway maintenance activities, one component of the basin's sediment budget. Over the long term, q_t would be compounded by the volume of tributary sediment that is transported directly from tributary canyons to the main channel as a result of headward migration of incision upstream of the highway and the loss of sediment storage capability of the floodplain and floodplain fans. Although the volume of lost storage associated with an individual floodplain fan may be small, the cumulative effect of lost storage and increased production of silt resulting from maintenance at every culvert is likely to further degrade aquatic habitat in the main channels.

Future geomorphic processes active in the modified system will depend on the sediment supply and transport rate, and flow magnitude and duration in the ephemeral tributaries and in the main river channel. The hydrologic character of the ephemeral tributaries investigated in this study suggests that there is an intermediate range of climatic events required to initiate headcutting and incision in the floodplain fan systems. At the lower limit, rainfall must at least exceed a threshold to generate runoff in the ephemeral tributaries. At the upper limit, runoff from the North Fork must be lower than that which inundates the highway and culvert system.

Finally, the rate of headcutting will depend on the presence of non-fluvial elements, such as large wood, that retard the processes and increase sediment residence time in the forested fans and floodplains. Results of this study suggest that large wood present as fallen logs, branches and stumps, as well as large-diameter living redwood trees, affects sediment storage on the fan and floodplain at the three study sites by diverting flow, stabilizing steps in the tributary and distributary channels on the fan, and by acting as dams that store sediment. Large redwood logs fallen across the tributary at Buried Log Gulch may retard the headward migration of the main step upstream of the managed baselevel change and may ultimately minimize the incision caused by baselevel lowering at this site. In contrast, the position of wood at Lost Gulch that is parallel to rather than perpendicular to the main tributary channel in the lower fan will allow headcutting to occur.

Management implications

Results of this study suggest that the influence of road maintenance excavation extends to floodplain and fan areas spatially removed from the road. As incision migrates upstream, it could eventually connect the tributary canyons and the entrenched upper portion of the fans to the main channel of the North Fork, providing a conduit for the rapid transport of sediment to the aquatic ecosystem of the North Fork and the Navarro River and bypassing the sediment storage function of the fan–floodplain system. Additionally, excavated silt placed on the floodplain next to channels could be easily mobilized by flood flows that inundate the floodplain, and provide a source of fine sediment to downstream reaches of the North Fork and Navarro River. Excessive fine sediment added to the aquatic system can degrade fish habitat by infiltrating into gravel bed material (Beschta and Jackson, 1978; Lisle, 1989) or by filling pools (Lisle and Hilton, 1999). Reduction in floodplain sediment storage due to road maintenance excavation has the greatest ecologic significance during small floods, when there is a sediment and water flux from the ephemeral tributaries to the floodplain, and sediment that was historically stored on the floodplain is more efficiently transported to the main river.

Highway 128 overlies various older footpaths, and stagecoach and logging roads that were present in the Navarro watershed prior to automobile use. Thus, road-related sediment sources probably have contributed sediment to the Navarro River and its tributaries for many decades. Other land uses including logging-related activities, especially unmaintained logging roads and culvert crossings on steep hillslopes, probably contribute much more sediment to the Navarro River than the Highway 128 tributary maintenance effects discussed in this paper. However, improved highway maintenance and management practices can help improve already degraded aquatic habitat. Management practices that could minimize the effect of culvert maintenance along Highway 128 on aquatic habitat include the following. First, raising the highway higher above the elevation of the floodplain, so that culverts under the highway are placed at the original grade of the tributary stream bed or floodplain, rather than excavated lower than the original thalweg so that maintenance does not require lowering the baselevel of the system. This would benefit water quality in the riparian system by maintaining the existing sediment storage capability of the floodplain–fans. Second, managing large wood on the floodplain to retard headcutting upstream of maintenance excavation could maximize sediment storage on the floodplain–fans. Finally, realignment of the highway off the floodplain to a former road location on the drainage divide that eliminates the need for culvert excavation maintenance in fan–floodplain systems, would benefit water quality so long as the new road alignment did not create new impacts. Problems associated with ridgetop roads such as concentration of drainage, initiation of landslides, and eventual integration of channel and road networks are identified by Montgomery (1994). Thus, the benefits of realignment must be evaluated in the context of geomorphic processes active in the entire basin. The data described in this study could aid in developing floodplain management and restoration strategies that accommodate geomorphic processes which allow floodplain–fan–sediment storage and which create and sustain habitat in the Navarro River or in other basins with forested floodplains.

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REFERENCES

Begin ZB. 1978. Aspects of Degradation of Alluvial Streams in Response to Base-Level Lowering. PhD Dissertation, Colorado State University, Ft. Collins, Colorado.

Begin ZB, Meyer DF, Schumm SA. 1981. Development of longitudinal profiles of alluvial channels in response to base-level lowering. *Earth Surface Processes and Landforms* **6**: 49–68.

Beschta RL, Jackson WL. 1978. The intrusion of fine sediments into a stable gravel bed. *Journal of the Fish Research Board Canada* **36**: 204–210.

Best DW, Kelsey HM, Hagans DK, Alpert M. 1995. Role of fluvial hillslope erosion and road construction in the sediment budget of Garret Creek, Humboldt County, California. In Geomorphic Processes and Aquatic Habitat in the Redwood Creek basin Northwestern California KM Nolan, HM Kelsey, DC Marron (eds). USGS Professional Paper 1454: M1–M9.

Brush LM, Wolman MG. 1960. Knickpoint behavior in noncohesive material: a laboratory study. *Geological Society of America Bulletin* **71**: 59–74.

Division of Water Rights. 1998. Report of Investigation of the Navarro River Watershed Water Diversion Complaint in Mendocino County. State Water Resources Control Board (SWRCB).

Entrix, Inc., Pacific Watershed Associates, Circuit Rider Productions, Inc., The Navarro Watershed Community Advisory Group, DT Sicular. 1998. Navarro Watershed Restoration Plan. Report prepared for Mendocino County Water Agency, The Coastal Conservancy and the Anderson Valley Land Trust.

Florsheim JL, Mount JF, Rutten LT, Larsen EW. 1998. Effect of road crossings on sediment storage and small tributary channel morphology on the Navarro River floodplain, California. *EOS Transactions American Geophysical Union* **79**(45): F348.

Furniss MJ, Ledwith TS, Love MA, McFadin BC, Flanagan SA. 1999. Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon and northern California. Water Road Interaction Series. San Dimas Technical and Development Center.

Gardner TW. 1983. Experimental study of knickpoint and longitudianl profile evolution in cohesive homogeneous material. *Geological Society of America Bulletin* **94**: 664–672.

Hagans DK, Weaver WE. 1987. Magnitude, cause, and basin response to fluvial erosion, Redwood Creek basin, northern California. In Erosion and Sedimentation in the Pacific Rim Proceedings of the Corvallis Symposium, August, 1987. IAHS Publication 165: 419–428.

Leopold LB, Miller JP. 1956. Ephemeral streams – hydraulic factors and their relation to the drainage net. USGS Professional Paper 282 A.

Leopold LB, Wolman MG, Miller JP. 1964. Fluvial Processes in Geomorphology. WH Freeman; San Francisco.

Lisle TE. 1989. Sediment transport and resulting deposition in spawning gravels, north coastal California. *Water Resources Research* **25**(6): 1303–1319.

Lisle TE, Hilton S. 1999. Fine bed material in pools of natural gravel bed Channels. *Water Resources Research* **35**(4): 1291–1304.

Montgomery D. 1994. Road surface drainage, channel initiation, and slope instability. *Water Resources Research* **30**(6): 1925–1932.

Muhs DR, Thorson RM, Clague JJ, Mathews WH, McDowell PF, Kelsey HM. 1987. Pacific coast and mountain system. In Geomorphic Systems of North America, WL Graff (ed.). Geological Society of America Centennial Special Volume 2: 517–581.

Pickup G. 1975. Downstream variations in morphology, flow conditions and sediment transport in an eroding channel. *Zietschrift fur Geomorphologie* N. F. **19**: 443–459.
Pickup G. 1977. Simulation modelling of river channel erosion. In River Channel Changes KJ Gregory (ed.) John Wiley & Sons: New York; 47–60.
Reid LM, Dunne T. 1984. Sediment production from forest road surfaces. *Water Resources Research* **20**(11): 1753–1761.
Schumm SA. 1993. River response to baselevel change: implications for sequence stratigraphy. *Journal of Geology* **101**: 279–294.
Sklar L, Dietrich WE. 1998. River longitudinal profiles and bedrock incision models: stream power and the influence of sediment supply. In Rivers Over Rock: Fluvial Processes in Bedrock Channels, Tinkler and Wohl (eds). Geophysical Monograph 107. American Geophysical Union: 237–260.
Weaver WE, Hagans DK, Popenoe JH. 1995. Magnitude and causes of gully erosion in the lower Redwood Creek Basin, Northwestern California. In Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin Northwestern California, KM Nolan, HM Kelsey, DC Marron (eds). USGS Professional Paper 1454: I1–I21.
Wemple BC, Jones JA, Grant GE. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Bulletin* **32**(6): 1195–1207.
Wolman MG. 1987. Sediment movement and knickpoint behavior in a small piedmont drainage basin. *Geografiska Annaler* **69A**(1): 5–15.

