GULLIES AND SEDIMENT DELIVERY AT CASPAR CREEK,

MENDOCINO COUNTY, CALIFORNIA

By

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ABSTRACT

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Nicholas J. Dewey

The Caspar Creek watershed, in coastal Northern California, features many gullies in its tributary valleys that deliver sediment directly into the perennial channel network. These gullies may help explain rates of sediment delivery in the watershed.

Sediment production from gullies responds to pulses in runoff. Resistant elements observed at headcut lips appear to slow the rate of headcut retreat temporarily until the elements are undercut. Headcut retreat occurs at both a gradual rate (0-15 cm yr^{-1}) in most headcuts and at a high rate (>1 m yr^{-1}) in a few. Banks, like headcuts, can fail suddenly or retreat gradually, and have an average retreat rate of 1.8 cm yr^{-1} in the observed cross sections. The amount of exposed vertical bank area in the watershed suggests that bank erosion may generate an important component of the sediment produced from gullies.

Gullying appears to have been accelerated after first-cycle logging, which occurred between 1860 and 1905. Erosion in the gullies is ongoing. Measured rates of headcut and bank retreat can account for more sediment than is exported past gaging stations. The gullies are large enough and young enough that their development would have generated a significant amount of sediment during their lifetime.

The impact of gullies on a catchment-scale sediment budget is enhanced by their ability to route sediment efficiently out of the watershed. A short-term (decadal scale)

sediment budget indicates that colluvial and alluvial deposits are likely to be accumulating sediment within subwatersheds, even as gullies evacuate sediment that has been in storage for thousands of years along the valley axes.

ACKNOWLEDGEMENTS

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INTRODUCTION

Overview

Channel erosion and sediment transport are critical components of sediment routing in a watershed. When channels are incising, routing can become more efficient, and the incising channels can also become an important source of sediment. The observation that widespread incision is occurring in a channel network is therefore of interest to those concerned with sediment outputs.

Gullies and incised stream channels characterize the Caspar Creek watershed, which drains to the Pacific Ocean between the towns of Ft. Bragg and Mendocino in Mendocino County, California. As part of Jackson State Demonstration Forest, Caspar Creek has been monitored since 1962 for the purpose of learning more about the impact of timber harvest and related activities on the landscape.

The entire Caspar Creek watershed was initially clear-cut and burned between 1860 and 1906. Second-entry logging occurred in most subwatersheds in either the 1970's (South Fork) or 1990's (North Fork). Some subwatersheds in the North Fork were left as mature second-growth controls.

Other studies of sediment production have been conducted at Caspar Creek. Gaging stations provide records of recent sediment output from tributaries at a temporal and spatial resolution that is unavailable for most watersheds. This study focuses on the role of gullies in sediment production, particularly those gullies that form the main channels of tributaries.

Channel incision is evident to casual observation throughout tributary watersheds of Caspar Creek. Gullies of a variety of sizes and morphologies are present in locations ranging from the crests of hilltops to third-order channels in the valley axes. Many of the most spectacular gullies are probably enlargements of small channels that occur along valley axes. These valley-axis gullies form much of the first- to third-order tributary channel system draining into Caspar Creek.

Although gullies and incised stream channels are widespread in the tributaries, the nature of channel incision in the watershed had not yet been the focus of a study. This paper describes the types of gullies found at Caspar Creek (with a focus on valley-axis gullies), describes their distribution, estimates rates of erosive processes, and evaluates the importance of valley-axis gullies as contributors of sediment to downstream reaches.

Background

Context of the Gully Study at Caspar Creek

Sediment pollution and soil erosion are of concern in Northern California for a variety of reasons. Chronic turbidity can have an adverse effect on salmonids and other aquatic biota (Henley and others 2000; Lisle 1989; Newcombe and MacDonald 1991; Sigler and others1984). Downstream river users and property owners may be concerned about impacts to the fluvial environment from upstream users. Loss of soils may be of concern to timber resource professionals because of implications for long-term site productivity.

In cases where there is concern about the impact of erosion and sedimentation, sediment budgets are often useful tools (Reid and Dunne 1996). However, it is important that assumptions underlying the sediment budgets are sound. For example, sometimes it is assumed that channels deliver sediment downstream at a rate equal to that at which they receive sediment from hillslopes, which they might be expected to do over the long term if a landscape maintains its form. Often, however, sediment follows a complex path through a watershed and is not delivered directly from hillslopes to the mouth of the basin (Trimble 1983). If channels are incising or aggrading, then those reaches of channel are delivering different amounts of sediment than they receive. This may be an important consideration in constructing a sediment budget.

One goal of the Caspar Creek watershed study is to better understand the effects of forestry on water quality in the Northern California coastal environment. One impact of concern is an increase in runoff in the years following a cut. Logging-induced loss of canopy interception may lead to substantially increased runoff at sites such as Caspar Creek (Reid and Lewis 2004). While buffer zones have helped reduce direct hillslope sediment inputs to channels, runoff pulses after logging are still routed through downstream channels. Lewis (1998) found that the watersheds that had the greatest increase in sediment production following logging were those where peak flows had also increased the most. Gully incision and growth provide mechanisms by which peak flow increases could increase sediment production.

About Gullies

Schumm (1999) defines gullies as dramatically incised channels that occur where there were no previous channels. He prefers the term “incised channel” for a preexisting channel that has downcut, and “composite incised channel” for a channel that contains both features. Schumm would describe the features at Caspar Creek as composite incised channels because they include both types. However, I will use the term “gullies” to describe dramatically incised channels of both types at Caspar Creek.

Incision of new channels may be initiated by surface scour, landsliding, or pipe failure (Bocco 1991; Dietrich and Dunne 1993; Jones 1971; Montgomery and Dietrich 1989; Swanson and others 1989). Downcutting of preexisting channels occurs either when erosive power increases or when the capacity of a channel to resist erosion is impaired, and a critical-power threshold is exceeded (Bull 1979). Whether prior surface channels existed or not, increased runoff can lead to gully development and channel incision. Gullies and incised channels can be persistent sediment sources and are frequently indicative of recent disturbances in a fluvial system (Bocco 1991).

After gullies incise, they continue to change in form and generate sediment. Graf (1977) proposed a negative exponential rate law describing the slowing of gully growth over time; he attributed this slowing to decreasing drainage area as the gully head moves upslope. Blong and others (1982) found that gully sidewall processes could produce substantial sediment following incision. Simon and Hupp (1986) propose six stages of incised channel evolution, during which sediment can be delivered to the channel by several different means, or else stored in aggrading phases. Their six suggested stages are: 1. Premodified: the state of the channel prior to disturbance; 2. Constructed: an anthropogenic stage of a modified non-equilibrium channel prior to degradation; 3. Degradation: the channel is actively downcutting but is not yet actively widening; 4. Degradation and Widening: the channel is continuing to incise while also undermining its banks and widening; 5. Aggradation and Widening: the channel has started aggrading again and banks are still receding; and 6. Quasi-equilibrium: the channel has reached a level where it is neither aggrading nor incising. Incision sets off a chain of events; not all sediment is produced in the initial incision process.

Schumm (1973) describes how a gully system can exhibit a complex behavior whereby portions of the network accumulate sediment from upstream gullies and aggrade until a critical steepness is achieved in the downstream end of the aggraded reach and new gully initiation occurs in the aggraded reach. By this mechanism, gullies may initiate in new portions of a channel network without any new disturbance.

Most studies of gullies have focused on locations where gullies are most noticeable, like deserts, grasslands, and recent fire sites (Graf 1979; Istanbulluoglu and others 2002; Oostwoud Wijdenes and Bryan 2001; Reid 1989; Seginer 1966; Vandekerckhove and others 2000). Gully research in timberland has often focused on the effects of roads. For example Croke and Mockler (2001) discuss interactions between gullies and roads on Australian timberland.

Research by Heede (1985) stands out as a study of gullying that resulted from upslope logging and was not tied to road building. Heede examined paired watersheds in the mountains of Arizona and found a downstream impact that was attributable to increased runoff induced by timber removal. He noted increased headcut migration in the logged watershed downstream of the buffer zone, which he attributed to a change in runoff.

Gullies have been noted as sediment sources in Northern California Franciscan basins. Best and others (1995) and Weaver and others (1995) document gullying after road-building and logging in the Redwood Creek basin in Northern California. Kelsey (1980) describes gullies to be significant sediment sources on hillslopes in Franciscan mélange in the Van Duzen basin. Though not studied in detail, gullies were identified as a sediment source to the South Fork of Caspar Creek as early as 1979 (Rice and others 1979).

Approach to Problem

This thesis describes the gullies at Caspar Creek, establishes their size and distribution, and assesses their relative importance in generating sediment. Gullies were mapped and described at a watershed scale, reach scale, and headcut scale to understand their morphology and distribution. Rates of gully erosion were estimated both by surveying features such as banks and headcuts and by comparing gully dimensions with estimated age of gullies. Stream gages in the field area provide tributary sediment production data to place gully sediment production in context.

The stream gages provide measurements of sediment yield, while hillslope data collected during other studies provide constraints on non-gully sediment inputs to channels. These two kinds of data are used in conjunction with gully mapping in five analyses: 1) Suspended sediment data recorded at nested stream gages are examined for evidence of sediment production along gullied reaches; 2) estimates of sediment generated from headcut and bank retreat are compared with rates of sediment production measured at stream gages; 3) long-term rates of sediment production are estimated from gully volume and estimated age, and compared with gage data; 4) the influence of hillslope erosion on sediment output is assessed; and 5) gully dimensions are compared with sediment yields.

FIELD SITE

Description

Caspar Creek drains coastal-belt Franciscan terrain between the Noyo and Navarro rivers in Mendocino County, California (Figure 1). The climate in the study area is coastal temperate, with precipitation concentrated in the winter months and averaging approximately 1200 mm annually.

The primary focus of the study is a set of gaged tributary channels, which drain watersheds ranging in area from 10 to 77 hectares. Stream channel flow becomes spatially intermittent within several hundred meters upstream of most tributary stream gages, even within a week after a winter storm. Subsurface pipe flow transports a substantial discharge of water out of upslope catchments (Ziemer 1992). The 1.5-year flood at the gages is approximately 0.004 $m^3s^{-1}ha^{-1}$.

The watershed is carved into uplifted marine terraces underlain by coastal-belt Franciscan greywackes and shales. The bedrock weathers deeply to form cohesive, clay-rich saprolites, which are more easily incised by the channels than is the unweathered bedrock. The clay-rich soils are largely Ultic Hapludalfs and Typic Haplohumults that formed in residuum (Dahlgren 1998). Channel cuts often expose bedrock and saprolite in the steeper valley-axis reaches.

Long profiles of the valley channels alternate between steep and low-gradient reaches, where alluvial fill accumulates. Alluvial deposits in these reaches are gravelly

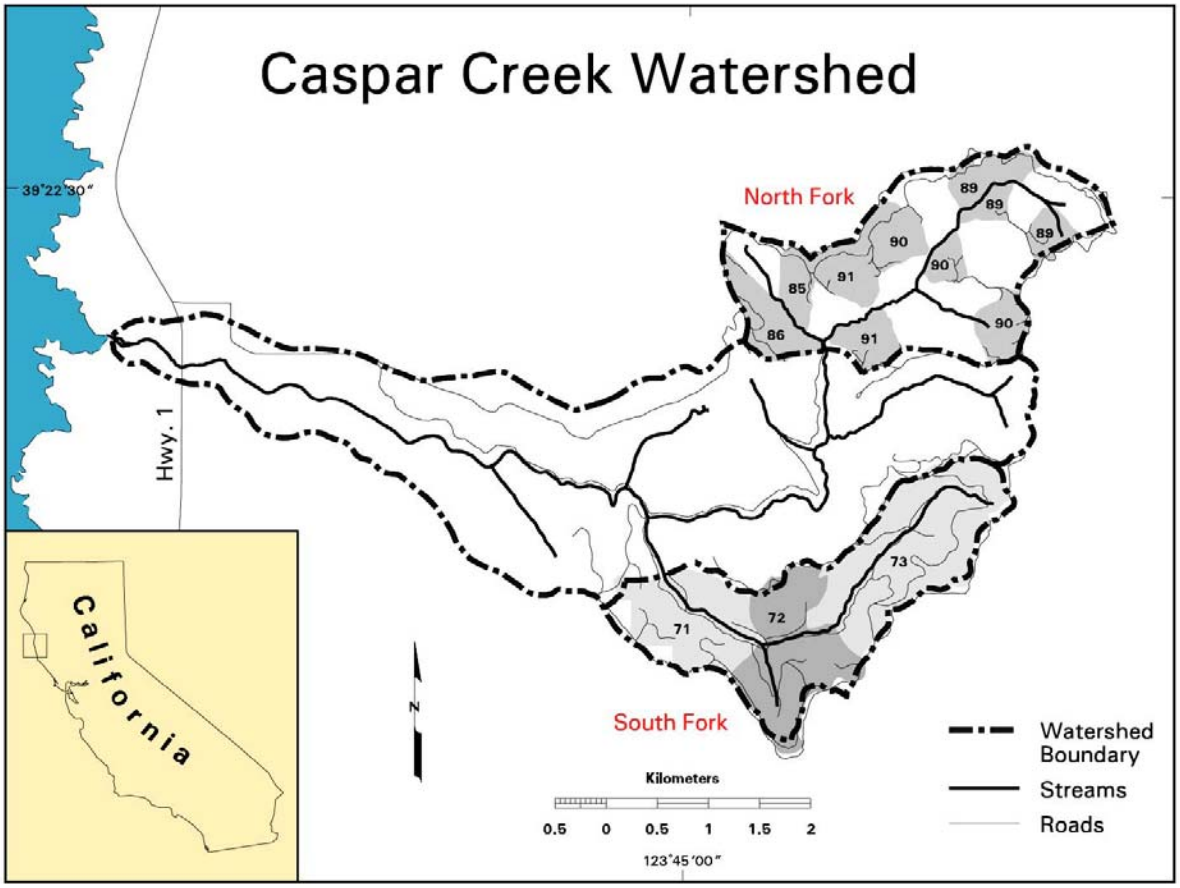

Figure 1. Site location map. The North and South Forks of Caspar Creek were both entirely clear-cut and burned between 1860 and 1905. Second entry logging dates are shown in the shaded areas.

and often well sorted. Many of the deposits appear to have been in place for millennia, showing significant secondary clay buildup between the gravel clasts and supporting old-growth root mats on the surface of the deposits. Poorly sorted debris flow deposits are also present but are less common than well-sorted alluvial deposits.

Vegetation consists largely of second- or third-growth mixed coastal redwood and Douglas-fir forest. Remnant stumps from the old-growth forest remain in growth position outside of the gullies. Many stumps have resprouted second-growth trees. In some less-active gullies, second-growth trees and other vegetation have become established.

Land-use History

The entire study area, with the exception of a few individual trees, was logged and broadcast burned between 1860 and 1904 (Napolitano 1996). Logs were generally dragged by oxen down to the main North and South Fork channels. Splash-dam floods were used to float logs downstream along the mainstem channels.

Logging and burning from the early logging heavily impacted the landscape, and yarding further impacted the waterways and valley axes. Significant sediment was delivered downstream after the initial entry logging. Aggradation over the last hundred years has largely filled in the Caspar Creek estuary. Concrete and wood structures associated with a former mill at the mouth of the Creek are buried under approximately a meter of accumulated sediment in some places.

In 1961, a joint federal and state study of the Caspar Creek watershed began. The state has sold timber from portions of Caspar Creek to timber contractors twice since it acquired the land, with the intent of studying the impact of logging techniques on the watershed.

The entire South Fork basin was selectively cut between 1971 and 1973, prior to forest practice rules requiring stream buffers. Although this second entry on the South Fork was a selective cut, yarding by tractor skidding was extremely disruptive to stream channels. Skid trails cross or coincide with stream channels in many places.

The North Fork was partially clear-cut between 1985 and 1991. Ridge cable-yarding was utilized, minimizing the need for tractor skid trails and access roads. Not all basins in the North Fork were harvested in this second entry. Some gaged subwatersheds (HEN, IVE, and MUN (Figure 2)) were left as mature second-growth controls.

Experimental Watershed History

This study focuses on tributary and headwater subwatersheds of the North and South Forks of Caspar Creek. Gullies were mapped in nine subwatersheds of the North Fork and nine subwatersheds of the South fork (Figure 2). Two of the nine subwatersheds of each fork are part of a nested pair where one gage is located upstream of another. The other seven tributary gages in each fork are single gages located in distinct watersheds. North Fork gage data were recorded for all mapped subwatersheds from 1985-1995, with some gages continuing to the present. Gage data have been recorded for

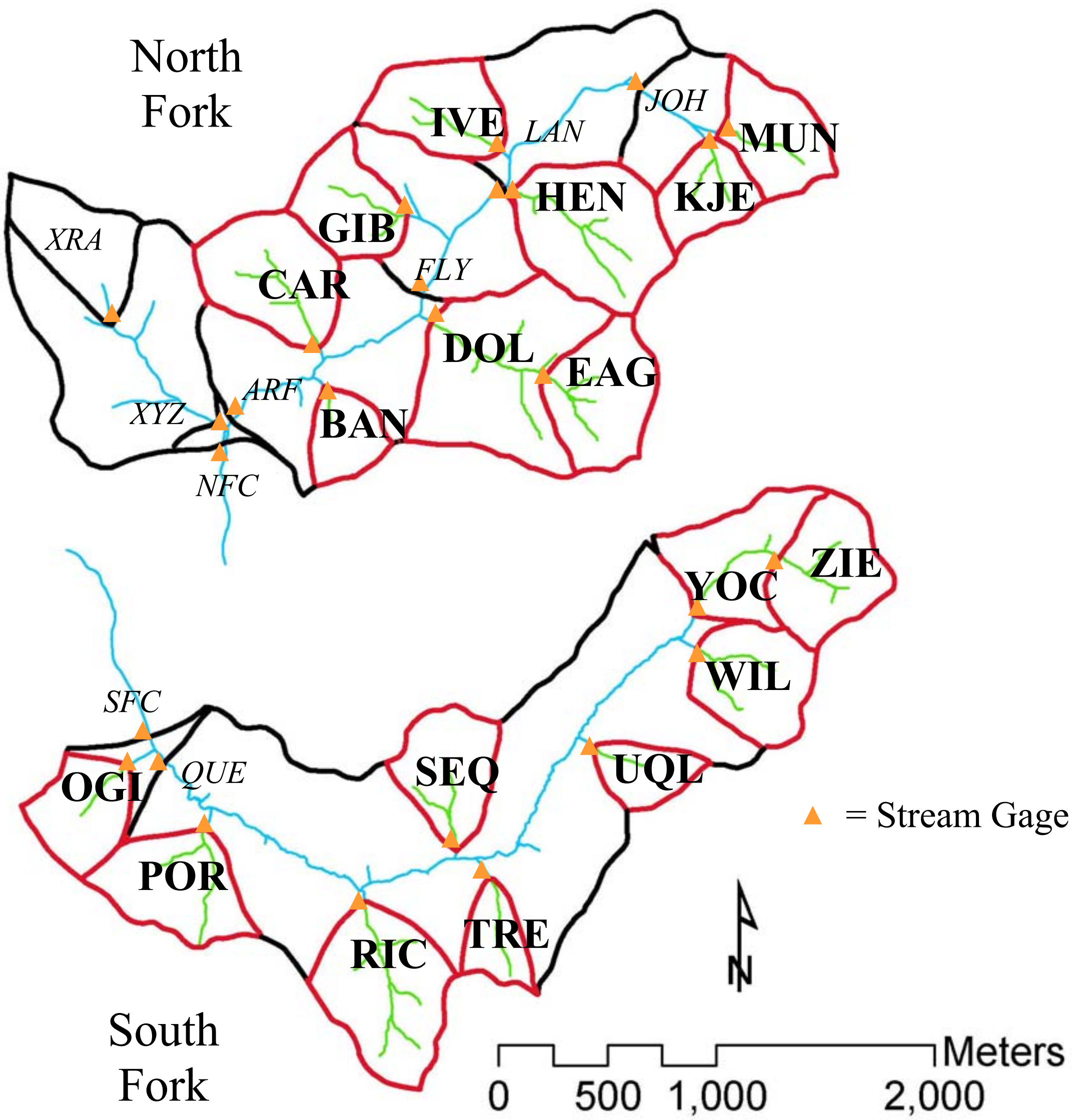

Figure 2. Map showing locations of study watersheds. The tributary watersheds in which gullies were mapped are indicated by bold print. Other gages are noted in italics. Some of these other gages are mentioned in this paper in reference to sediment output data.

all mapped subwatersheds of the South Fork starting in Water Year 2001. Selection of time frames for examining gage data is based upon years for which data are available.

Study subwatersheds range in area from 10 ha in tributary BAN to 77 ha in tributary DOL (Table 1). Valley-axis slopes range from about 3 to 35 percent; hillslope gradients can exceed 70 percent.

The subwatersheds can be divided into four categories, based on land-use history. The nine subwatersheds in the South Fork were selectively cut and tractor-yarded in the 1970's. Five of the subwatersheds in the North Fork were clear-cut in the 1990's and predominantly cable-yarded. Three North Fork subwatersheds are controls, which have not been logged since the initial logging between 1860 and 1905. One North Fork subwatershed (DOL) is a mix between the control and clear-cut categories: the portion of the watershed above gage EAG was clearcut while the downstream portion was left uncut. The control subwatersheds provide an opportunity to assess the impacts of initial entry logging without overprinting by second entry logging.

Table 1. Tributary summary with second-cut logging dates.

Gage	Fork	Area (ha)	Year of 2^{nd} Cut	Notes
BAN[1]	**NFC**	**10**	**1991**	
CAR	**NFC**	**27**	**1991**	
DOL	**NFC**	**77**	**1990 (Just EAG)**	**Contains EAG**
EAG	**NFC**	**27**	**1990**	**Subset of DOL**
GIB	**NFC**	**20**	**1990**	
HEN	**NFC**	**39**	**No 2^{nd} Cut**	**Control**
IVE	**NFC**	**21**	**No 2^{nd} Cut**	**Control**
KJE	**NFC**	**15**	**1989**	
MUN	**NFC**	**16**	**No 2^{nd} Cut**	**Control**
OGI	**SFC**	**18**	**1971**	**Private reservoir in upper basin.**
POR	**SFC**	**32**	**1971**	
RIC	**SFC**	**49**	**1972**	
SEQ	**SFC**	**17**	**1972**	
TRE	**SFC**	**14**	**1972**	
UQL	**SFC**	**13**	**1973**	
WIL	**SFC**	**26**	**1973**	
YOC	**SFC**	**53**	**1973**	**Contains ZIE**
ZIE	**SFC**	**25**	**1973**	**Subset of YOC**
XYZ	NFC	77	Parts 1985-1986	Big landslide in 1995. Contains area formerly labeled as basin Z (not ZIE).
XRA	NFC	18	No 2^{nd} Cut	Subset of XYZ. A control; also upstream of 1995 landslide in logged part of XYZ.
ARF	NFC	384	Parts 1989-1991	NFC above XYZ confluence and pond.
NFC[2]	NFC	473	Parts 1985-86, 1989-91	All NFC (below pond)
SFC[2]	SFC	424	1971-1973	All SFC (below pond)

[1] Bold print indicates gages on tributaries in which gullies were mapped.

[2] Gages NFC and SFC are downstream of all the tributaries in their respective forks.

Gage Records

The stream gage records at Caspar Creek allow for a more detailed examination of role of the gullies in producing sediment than would otherwise be possible. Suspended sediment data are summarized for the years that they are available (Table 2). Suspended sediment is assumed to account for over 75% of sediment yield from each subwatershed (Rice 1996, Napolitano 1996). These data show both fluctuations and some continuity in the behavior of each channel as a sediment producer. Plotting of cumulative suspended sediment production through time shows trends in production from each tributary relative to other tributaries (Figure 3). There is some continuity in the suspended sediment output of channels over time; of the five gages monitored from 1986-1995 that were still monitored from 2001-2003, four showed a similar pattern of relative suspended sediment production, with the exception of EAG increasing dramatically from the first to the second time period relative to the others (Figure 4). This paper compares these sediment production data with gully dimensions and observations of gully headcut and bank activity, as well as with other sediment input data, to assess the gullies' possible role in producing sediment.

Table 2. Estimated storm suspended sediment production (kg $ha^{-1}yr^{-1}$) by year in gaged tributaries cited in this paper.

Gage	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
BAN	34	7	11	10	39	3	12	150	39	159	NA	NA	NA	NA	NA	NA	NA	NA
CAR	119	8	40	23	182	1	70	443	48	572	169	364	527	421	44	25	95	219
DOL	576	40	96	63	458	8	157	3219	63	1768	606	2669	2172	1109	263	48	457	911
EAG	267	14	42	30	382	2	59	709	65	1651	1177	3452	1554	998	144	52	232	1375
GIB	231	25	40	34	92	8	69	718	58	619	NA	NA	NA	NA	NA	NA	NA	NA
HEN	210	16	48	40	403	1	18	712	11	802	152	1136	796	658	98	34	216	229
IVE	241	10	31	25	122	2	6	156	7	155	44	169	193	131	46	11	77	105
KJE	1543	95	523	296	1812	14	117	1063	80	1148	NA	NA	NA	NA	NA	NA	NA	NA
MUN	403	33	127	48	407	2	39	542	22	525	NA	NA	NA	NA	NA	NA	70	NA
OGI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	46	238	374
POR	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	119	611	678
RIC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	31	128	308
SEQ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	64	466	768
TRE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	112	252	361
UQL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	13	64	52
WIL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	37	150	272
YOC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	66	382	722
ZIE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	34	121	139
XYZ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	50	191	329
XRA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	252	426

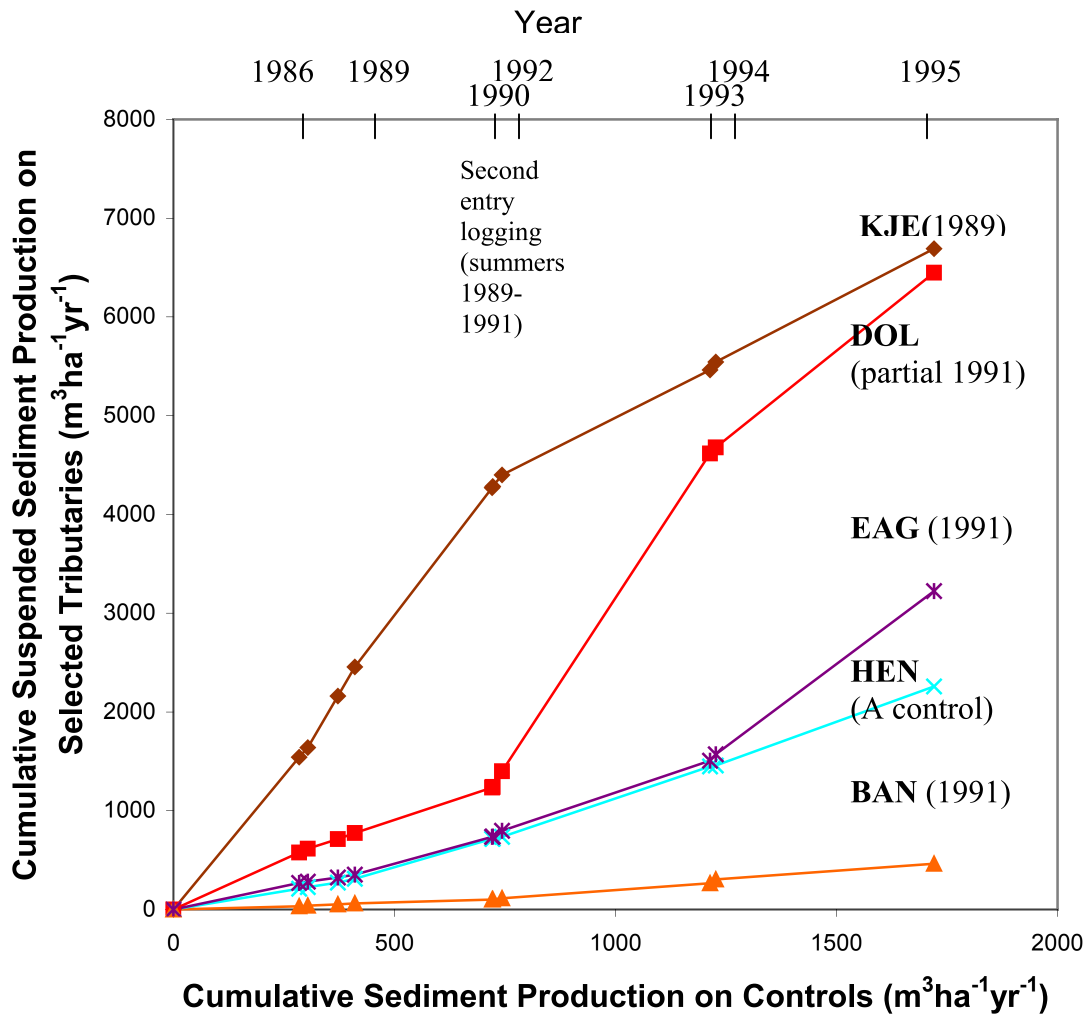

Figure 3. Cumulative sediment yield curves for five tributaries for period 1985-1995. Year of logging in each tributary is in parenthesis. 1991 was a very dry year and did not produce sediment at a level that registers on the scale of this graph.

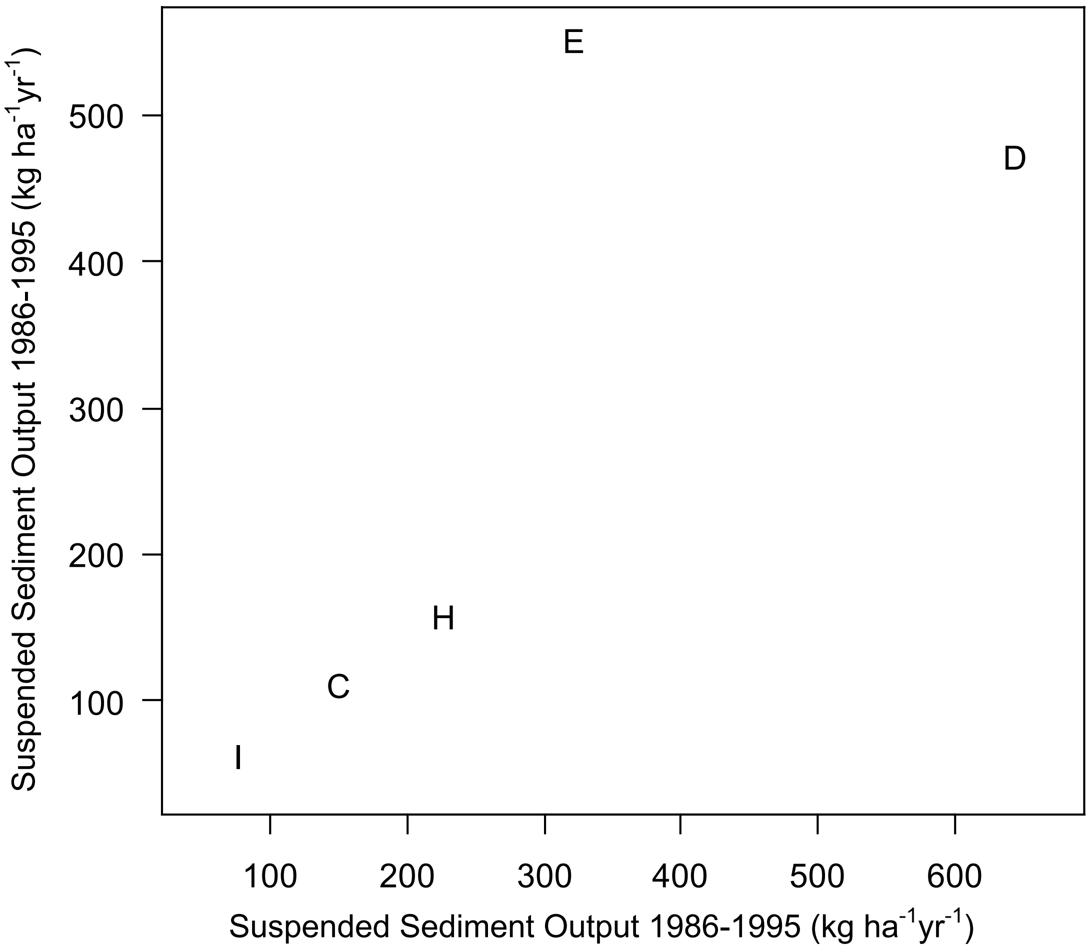

Figure 4. Comparison of suspended sediment production between different time periods for the North Fork tributary gages that were maintained during both time periods. (In this and subsequent figures where one letter is used to represent a gage, the letter represents the first letter in the gage name.)

METHODS

Strategy

Several types of data are used to describe and assess the importance of gullies as sediment contributors: 1) extent, dimensions, and description of the gullies; 2) erosion rates from gullies; and 3) tributary sediment yields and hillslope sediment production rates. Gullies were described and dimensions and locations measured in gaged tributary subwatersheds of both North and South Forks. Erosion rates were estimated both by a short-term approach of surveying gully features, and by a longer-term approach of comparing gully dimensions to estimated age. Previous work by other researchers affiliated with the Caspar Creek Experimental Watersheds allowed for estimation of hillslope inputs and sediment yields at gaging stations.

Gully Mapping

A special focus was given to mapping valley-axis gullies as these are more active, show more consistent flows, are easier to map thoroughly, and are more hydrologically connected to stream gages than hillslope gullies. The descriptor "valley-axis" should not be thought of as limited to flat valley bottoms, but includes axes of low-order hollows (typically with drainage area of 1 to 4 ha and a slope around 30%) that are concave in nature and connected by mostly continuous channels to the downstream channel network.

Generally, within each subwatershed one or more channels were mapped up to or past a point above which the majority of valley axis was either unchanneled or characterized by inactive channels in which duff had built-up and secondary vegetation had established itself. More than one channel was followed up to this point if tributary channels appeared of similar magnitude at their junction.

In some third-growth North Fork channels it was impractical to reach a point above which a majority of the valley axis could clearly be said to be unchanneled, due to thick slash impeding movement and viewing of channels. Of the five North Fork third-growth watersheds, GIB and BAN were followed with confidence to the point where a continuous channel ceased. KJE was followed to the apparent upper end of the continuous surface channel in an area where the valley axis was predominately characterized by pipe hole collapses separated by unincised reaches. However, upstream of this point surface channels were seen coming out of pipe openings and then disappearing under slash; these did not connect with downstream surface channels. In CAR and EAG, a significant headcut downstream of a major depositional reach was selected as the top of the mapping reaches. These sites were upstream of channels determined by forestry workers to be large enough to require buffer zones, but downstream of smaller gullies that were still largely continuous and would have been followed had vegetation and time permitted. In any case, the sizes of the channels surveyed downstream of the depositional cutoffs in CAR and EAG are significantly larger than those observed upstream.

Upstream of mapped reaches are some inactive gullies, evidence of pipe collapse, and some short stretches of active channel which empty onto small depositional fans. Many upslope hollows that were not mapped were walked and observed. The importance of hillslope gullies in long-term landscape evolution and delivery of sediment to hollows and valleys is not to be discounted, but a goal of this study was to map and understand gullies that were integrated into continuous, or mostly continuous, channels connected to gages.

Methods of Surveying

In the South Fork, channels had not been previously mapped and were mapped for this project. Channels were mapped and gully dimensions were measured using compass, tapeline, stadia rod, and hand-level. Mapping consisted of measuring bank-to-bank width and bank-to-thalweg depth, as well as position of the channel relative to an inclined taut tapeline. The tapeline was tied to benchmarks. Headcut locations and vertical drop were noted and measured; headcuts were used as breakpoints for assessing channel depth to complement measurements of bank-thalweg depth measurements taken above and below headcuts.

In the North Fork, channels had been mapped previously by U.S Forest Service Pacific Southwest (PSW) Research Station workers utilizing tape and compass as well as laser theodolite techniques. I used these as base maps and surveyed bank-to-thalweg depth and checked bank-to-bank width along the channels. As in the South Fork, headcut locations were noted for this study and used as breakpoints for calculating channel depth.

Two reaches were mapped differently than the rest of their respective forks. One reach comprises the mainstem channel in Watershed YOC and the lower part of ZIE in the South Fork. The other reach comprises part of MUN in the North Fork. These reaches were selected as survey areas for headcuts and cross sections, and were initially mapped with a laser theodolite. Cross sections were measured later in these reaches using a stadia rod.

Width and left- and right-bank-to-thalweg depth of gullies were noted at 1,074 locations along 3,340 meters of valley axis in nine gaged tributaries of the North Fork, and at 2,124 locations along 5,670 meters of valley axis in nine gaged tributaries of the South Fork. These data were used to estimate gully volume and bank area and to calculate width-depth ratios. An average of left- and right-bank-to-thalweg depth was used for purposes of calculations of width/thalweg depth ratios.

Slope and Drainage Area Calculations

Slopes and drainage areas were estimated in order to examine thresholds of incision and deposition. Slopes were estimated in the South Fork by using a clinometer as the channels were mapped. In the North Fork, slopes were estimated by using preexisting survey data. The slope data is slightly sparser for the North Fork, but slopes appear similar and tend to show inflection points at similar spacing to those found in the South Fork. These inflection points often correspond to confluences with swales. Drainage area was estimated using a 10-meter digital elevation model, and was calculated for locations of headcuts larger than 0.7 meters, tops of mapped channels, depositional areas, and at

50-meter intervals along channeled portions of each valley axis starting 25 meters upstream from each stream gage.

Monitoring Gully Erosion

Overview

Some sites in tributaries YOC, ZIE, and MUN were selected for detailed headcut and cross-section monitoring. Seginer (1966), Oostwoud Wijdenes and Bryan (2001), and others have estimated headcut retreat rates by repeated surveying. I attempted a similar approach.

Headcut progress between 2000 and 2002 was measured, with some follow-up work in 2003 and 2004. Several methods, including a laser theodolite survey, a tape survey, and follow-up visual observations, were employed to describe headcuts and establish whether headcuts changed or not over this time period. Tape surveys were also used to describe and measure changes in cross sections between 2000 and 2002.

The study period (2000-2004) includes some storms that would be considered geomorphically significant, but no storms that exceeded a 5-year recurrence interval in magnitude. Winters of 2002 and 2003 included two storms of recurrence intervals of 2 to 3.5 years, with the largest storm occurring in the winter of 2003. Some changes in channel morphology thus could be reasonably expected during the study period.

Laser Theodolite Surveys

The laser theodolite allows survey of points on the face of the headcut, which on many headcuts is underneath an overhanging lip and difficult to survey by a top-down tape-line method. Five headcuts were surveyed in greater detail than others by laser theodolite and were selected for resurvey in 2002. The headcut shape was defined by shooting a cloud of points on the headcut face, plunge pool, banks, and thalweg upstream and downstream, and tying these points into benchmarks. The follow-up surveys concentrated most heavily on the headcut face and on details in areas that looked most likely to have changed.

Lower resolution surveys of 40 headcuts were carried out by surveying the thalweg above and below the headcut with a laser theodolite, along with the lip of the headcut and occasional banks or other nearby features. While these surveys were judged not sufficient to detect subtle motion, they would be sufficient to detect more dramatic changes. These headcuts did not appear to move by 2002 and were not resurveyed, as it was judged that any movement that might have occurred would not have been picked up by the low-resolution survey. In many of these cases, movement that might have occurred would have been confined to the face of the headcut, which usually was not surveyed. One of these headcuts, ZIE 50, was observed during a field outing to have moved noticeably in the winter of 2004: part of the bank containing a survey pin had collapsed into the channel.

Tapeline Surveys

Transects surveyed by measuring down with a stadia rod from a tapeline strung obliquely across a headcut provide a precise measure of change but do not record changes below undercut banks and can miss changes elsewhere. This method was probably most valuable for detecting bank failure or channel scour upstream and downstream of headcuts.

Analysis of Suspended Sediment Transport Data at Gaging Stations

I used discharge and suspended sediment data collected at gaging stations and analyzed by the PSW Research Station (Lewis 1998; Lewis and others 2001). Automatic sediment samplers at each stream gage are activated when storm flows exceed a threshold and are programmed to sample at certain levels of turbidity, which is recorded continuously. Transport rates are computed from discharge and calibrated relations between turbidity and suspended sediment concentration.

To calculate annual storm sediment totals, sediment generated in storm events is summed. Large storm events produce on the order of 100 times the sediment recorded during smallest events that exceed the storm-stage threshold, storm data generally cover a time period comprising 5-10 percent of the winter. Because annual suspended sediment output from these small catchments is so strongly weighted towards the largest storms, measured storms account for 90-99% of sediment output in most years (Lewis 2007), although the percentage may be less in years with small storm flows.

Sediment data from a few (usually smaller) storms were missing from the data set on each tributary. Missing storm loads were calculated using relations between peak flow and total sediment transport for each storm. Relations based on peak flow had a better correlation with the sediment transport than total storm flow, but relations using total storm flow were used in a few cases when peak flow was not available. Data are available for most large storm events in the tributaries. Suspended sediment loads estimated in this fashion accounted for less than 5% of the total sediment load.

Bedload is not included on Table 2. In his analysis of surface erosion, Rice assumes that bedload is 33% of suspended load or 25% of total load (Rice 1996). This figure is similar to Napolitano's estimate of 27% gravel content in sediment output from source channels (Napolitano 1996).

RESULTS

Overview

Results of the study can be divided into three broad categories. First is a description of the kinds of gullies present and their distribution within the study area. Second is a summary of estimations of erosion rates in the gullies. The third part of the results is an assessment of the importance of the gullies as sediment producers within the watershed.

Gully Survey

Description of the Gullies and Associated Features

Gullies. Gullies take a wide variety of forms in the Caspar Creek watershed. In many reaches channel incision occurs as a series of gullies between closely spaced headcuts. In these cases the channel may be either continuous (Figure 5) or discontinuous (Figure 6). Other reaches are continuously incised for over 50 meters with one dominant headcut marking the top of the gully (Figure 7). The gullies mapped for this study appeared to be actively eroding, but many inactive gullies that were not mapped are also present. The inactive reaches are usually upstream of the mapped reaches, but in some cases the active gullies are nested inside of inactive gullies. Inactive gullies feature duff infill and a higher incidence of second-growth vegetation than active gullies, but they still apparently post-date initial entry logging (Figure 8).

In cross section, active gullies feature a low width-depth ratio; the median observed ratio of bank-to-bank width divided by average bank-to-thalweg depth

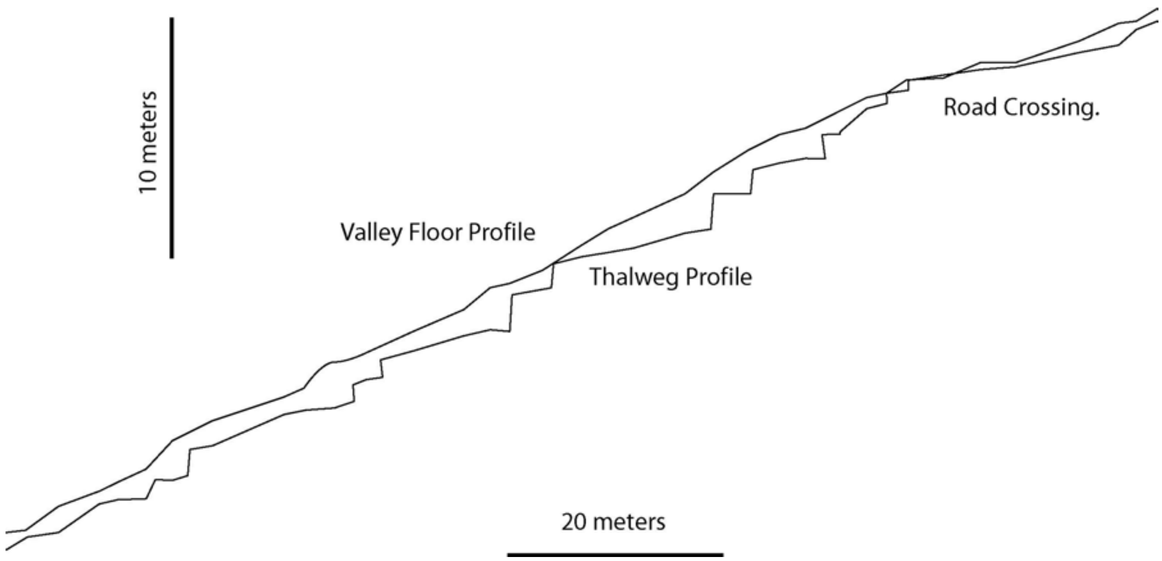

Figure 5. An almost continuously channeled reach in tributary WIL featuring multiple headcuts delineating locations of deep incision. The channel here is typically 1 to 2 meters wide (width/depth ratios of 1 to 3), with fresh headcuts. Downstream of here the flow goes subsurface under a road crossing before the confluence with the other fork of tributary WIL.

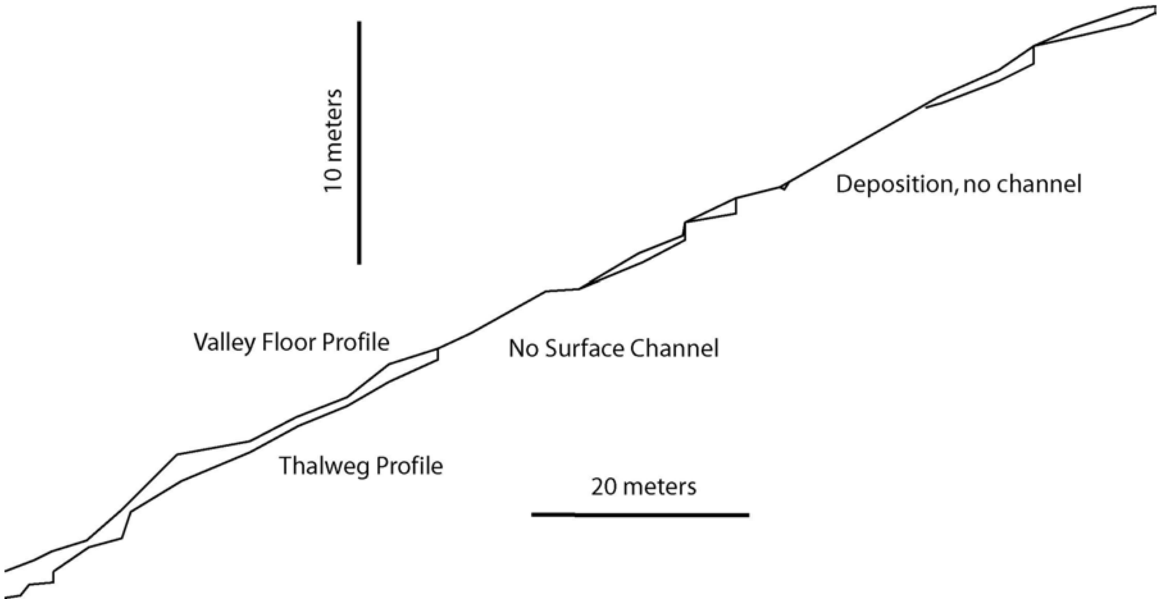

Figure 6. Long profile of a reach of discontinuous small gullies in the upper drainage of the SEQ subwatershed. No channel is evident where there is only a valley floor line (one line) present. Identification of channel head location is complicated by the presence of discontinuous reaches like this.

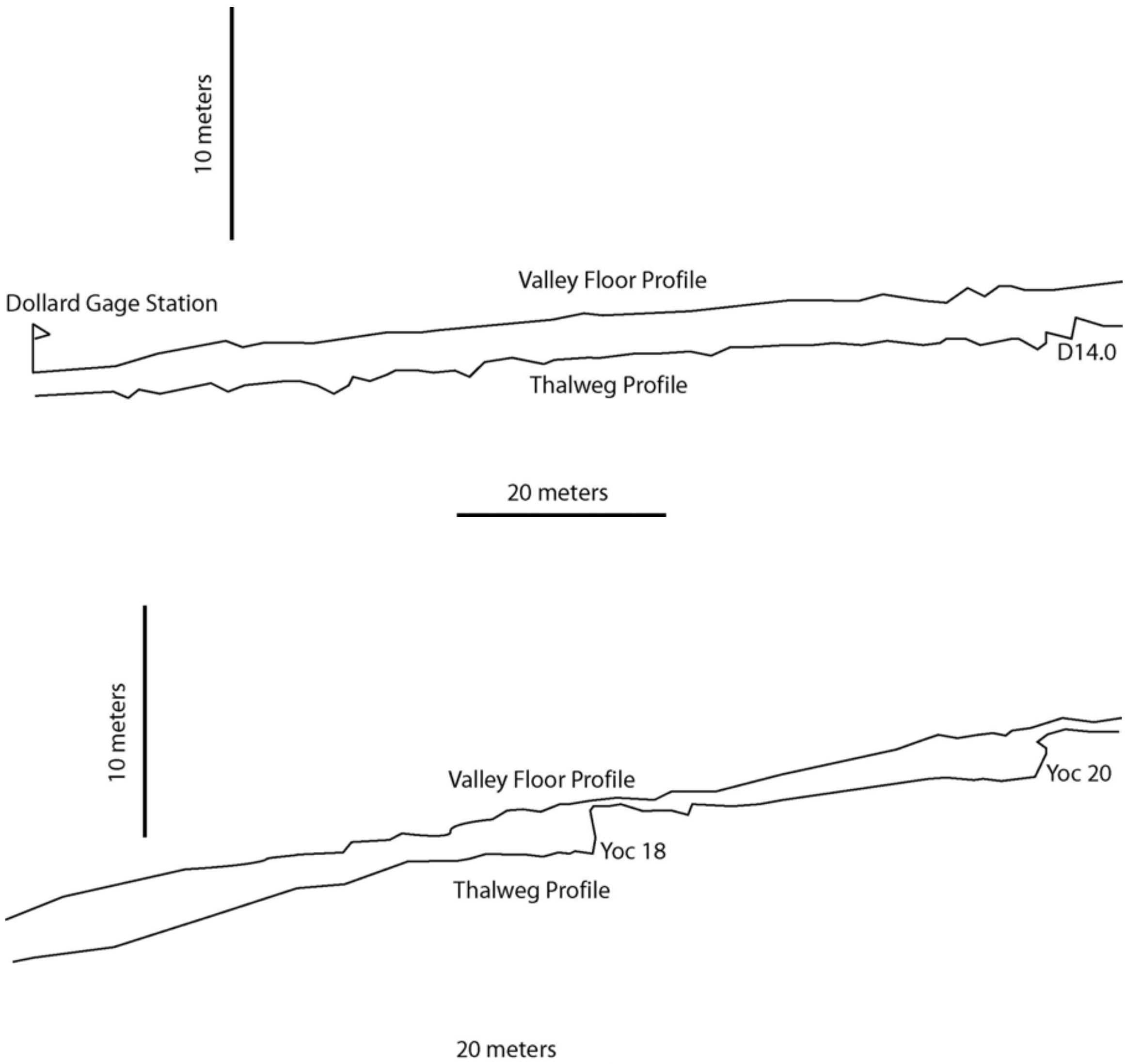

Figure 7. Long profiles of reaches of continuously incised channel in DOL and YOC.

Figure 8. This older gully, with receding non-vertical walls, supports vegetation but not yet any mature trees. Most gullies look fresher than this one, even in control watersheds, but this gully still appears to post-date logging. A small active channel cuts the floor of the gully, and farther upstream the gully walls are actively eroding.

is1.8. For convenience in sampling, this figure is based on thalweg depth, rather than the more frequently used average depth; however, most of these channels have nearly rectangular cross sections, and such a low ratio represents an incised channel. Walls are nearly vertical to overhanging (Figure 9). The steepness is maintained by bank undercutting from channel erosion. Rooting layers jut out over the banks in many places (Figure 10) and form a complete roof over the gullies in some places (Figure 11). In some cases where there are multiple headcuts, the channel is incised both upstream and downstream of a headcut (Figure 12). Within large gullies, small headcuts can be seen migrating up the floor of the gully towards the dominant headcut that defines the upstream extent of the gully (Figure 13).

In-place old-growth wood is limited to areas outside of the deep gullies, though some shallow gullies have not cut completely through the rooting layer so flow occasionally spills over old-growth roots that form headcut lips. Many old-growth stumps are located along gully banks and are at various stages of being undercut and falling into channels (Figure 14). In some cases, active gullies dissect the floor of older gullies that also appear to post-date initial entry logging.

Much of the substrate excavated by the gullies had apparently been in place prior to incision for a considerable period of time. Many old-growth stumps are now undercut by gullies, indicating that valley fill had been in place long enough to support old-growth trees. The exposure of grey clay horizons in the wall of gullies suggests that former water tables were positioned a meter or two above the current water table long enough for gleyed clays to form, a process that probably takes at least a thousand years (Rose and

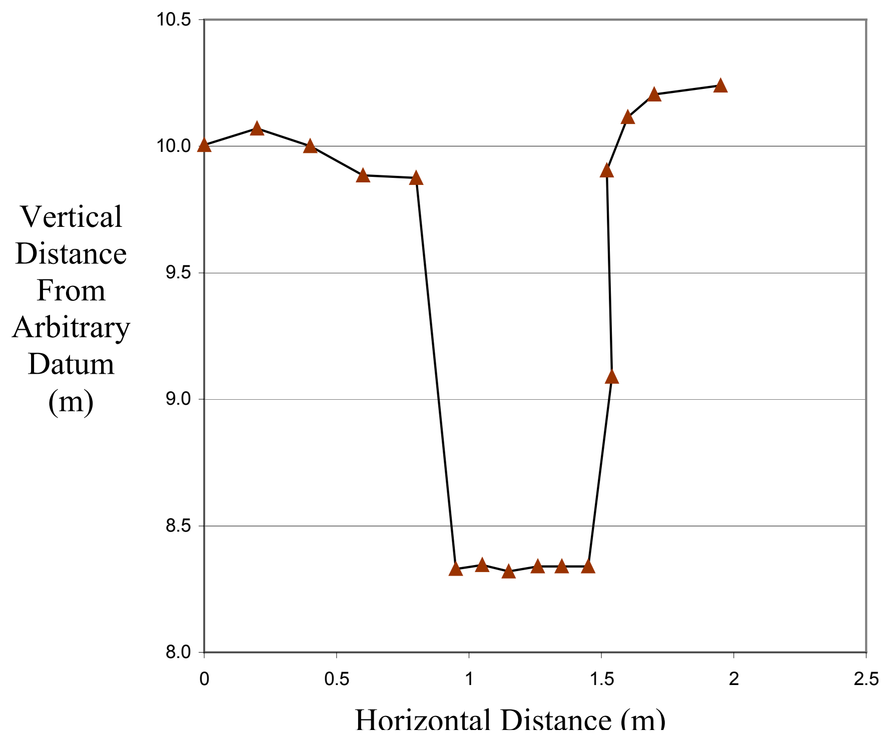

Figure 9. A cross section from tributary YOC, just downstream from headcut YOC 12. Note the deep, narrow form (no vertical exaggeration). Parts of the banks are overhung by the surface root mat here.

Figure 10. A headcut in tributary MUN. Notice the overhanging root mat as well as the accumulation of roots and small woody debris (held in place by roots) at the lip of the headcut.

Figure 11. A roof of roots from upright stumps hangs over a gullied channel in tributary CAR. The channel cuts down to bedrock that camera case rests on.

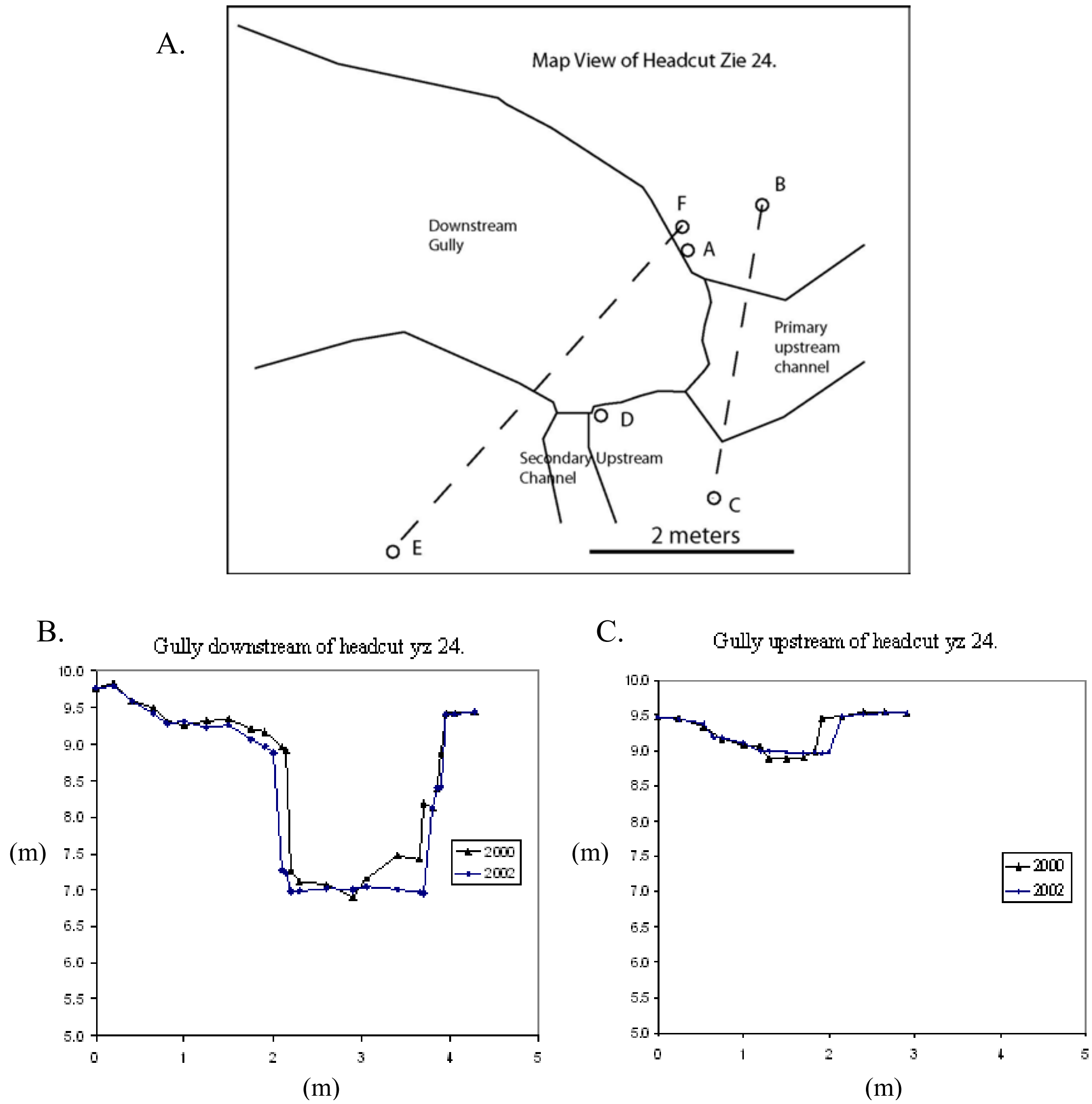

Figure 12. (A) Map of Headcut ZIE 24, and cross sections downstream (B) and upstream (C) of the headcut. A small gully spills over the headcut into a larger gully.

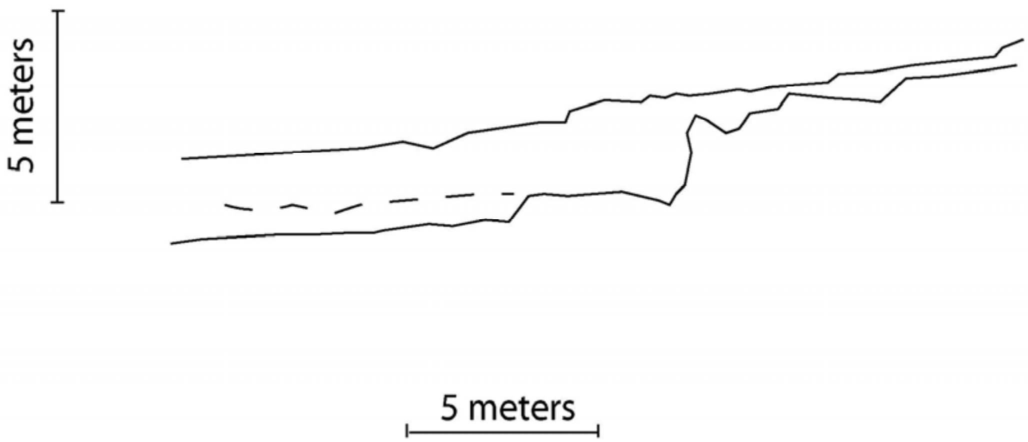

Figure 13. Profile view of headcut MUN 12. Note the small headcut within the gully downstream of the larger headcut. The dashed line represents the inner bank around the nested gully. Roots are responsible for the odd profile geometry at the lip of the larger headcut.

Figure 14. A large stump, tilting in from the bank of KJE channel, appears to be on the verge of toppling into the channel if the bank continues to recede. The gully here is over 3 meters deep, and the bank underneath the overhanging root layer is approximately vertical. Some material is accumulating along the base of the bank wall.

others, 1988). Such a drop in the water table is consistent with gully erosion. Even in cases where more recent alluvium is cut by gullies, as in the lower reach of tributary DOL, the gullies cut through the young deposits into deeper, older deposits in many places (Figure 15).

Valley-axis gullies dissect both inner gorge reaches and valley flat reaches. In both cases they cut beneath valley fill sediments in places. In inner gorge reaches it is not surprising that gullies cut into saprolite and crumbling bedrock, but even some valley flat reaches appear to have fairly thin soils overlying weathered bedrock, as evidenced by bedrock exposures in headcuts near the downstream reaches of valley flats. One such location is near benchmark M01 in the MUN watershed, where bedrock is exposed in most of a headcut face at the downstream end of a depositional reach.

Depositional reaches. The tributary channels show signs of incising over much of their length, but there are also some reaches in the tributary valleys where sediment accumulates. The distribution of these depositional reaches may be an important influence on sediment routing through these watersheds.

Three types of depositional reaches were observed. One type features the channel braiding downstream and disappearing into an unchanneled reach and then reappearing along the valley axis downstream below a headcut. A second type is continuously channeled, but the channel is aggraded in places and spills out easily onto a floodplain. This second type of reach obviously passes channeled flow containing both suspended and bedload sediment, but also stores sediment on the floodplain, particularly during high

Figure 15. The layer under the buried former land surface (visible as exposed roots in the wall) in DOL tributary is rich in reduced grey clays. The modern water table is lower than the former water table. Translocated oxide-rich clays drip out of pipes on the reduced headcut face. Pipes have not yet formed at the level of the current water table.

flow events. A third type of reach is contained within defined channel banks, where sediment accumulates behind wood or rocks that have fallen into the channel. In this case, flow often percolates through the sediment accumulation, potentially filtering out some of the fine sediment load.

Soil Pipes. As documented by other workers (Ziemer 1992; Keppeler and Brown 1998), soil pipes are widespread at Caspar Creek. Pipes are evident upstream of the active channel network, and they often directly underlie surface channels. Pipe openings occur in most headcut faces as well as in gully walls. Tributary drainages that lack surface channels are often apparently connected to the main channel through soil pipes. Pipes are related to the formation of some gullies. For example, part of a large gully upslope of gaging station EAG appears to be a collapsed pipe. It is possible to crawl through the pipe for about 10 meters at one location between two daylighted reaches of the gully. Pipe flow has been found to contribute to gully formation at other localities (Jones 1971; Swanson and others 1989).

In the smallest watersheds, pipes appear to be the main conduits for water and sediment even where surface channels are present. In some cases a channel (either dry or wet) directly overlies a pipe that carries water. Pipe outlets can be seen at frequent intervals on gully walls and headcut faces. These pipe outlets are often part way up a bank or headcut face that contains gray reduced clays suggestive of having formerly been saturated. Collapsed pipe roofs in the upper reaches of the watersheds leave daylighted channels with headcuts.

Distribution of Gullies and Related Features

Gullies are widespread in valley axes and form most of the tributary drainage network. All the tributary channels are incised over a large portion of their lengths, with multiple headcuts forming significant elevation drops (Figures 16 a-b and 17 a-b). Long, deeply gullied reaches (as in KJE and lower DOL) form spectacular gullies without a high density of headcuts per unit channel length. Observations of each tributary are summarized on Table 3.One way to examine gully distribution is by testing for a stream power threshold distinguishing channeled and unchanneled reaches and headcut locations. Stream power is a function of discharge and slope, with drainage area providing a proxy for discharge. Slope and drainage area were measured for all headcuts greater than 0.7 m in height, the top-most mapped headcut in each drainage, depositional reaches, and headcuts at the base of selected depositional reaches (Figure 18). The occurrence of gullies and depositional reaches appears to be controlled by a stream power threshold. Measurements of slope and drainage area were also compared with channel depth at 50-meter intervals along channels. Larger drainage areas and steeper slopes tend to support deeper gullies (Figure 19).

A higher stream-power threshold appears to exist for formation of gullies that extend more than 20 meters downstream of their headcuts than for shorter gullies (Figure 20). This may be because in locations of high stream power, sediment is more easily transported and does not fill the channel immediately downstream of the headcut. This may also reflect headcuts that have migrated farther over the duration of their existence.

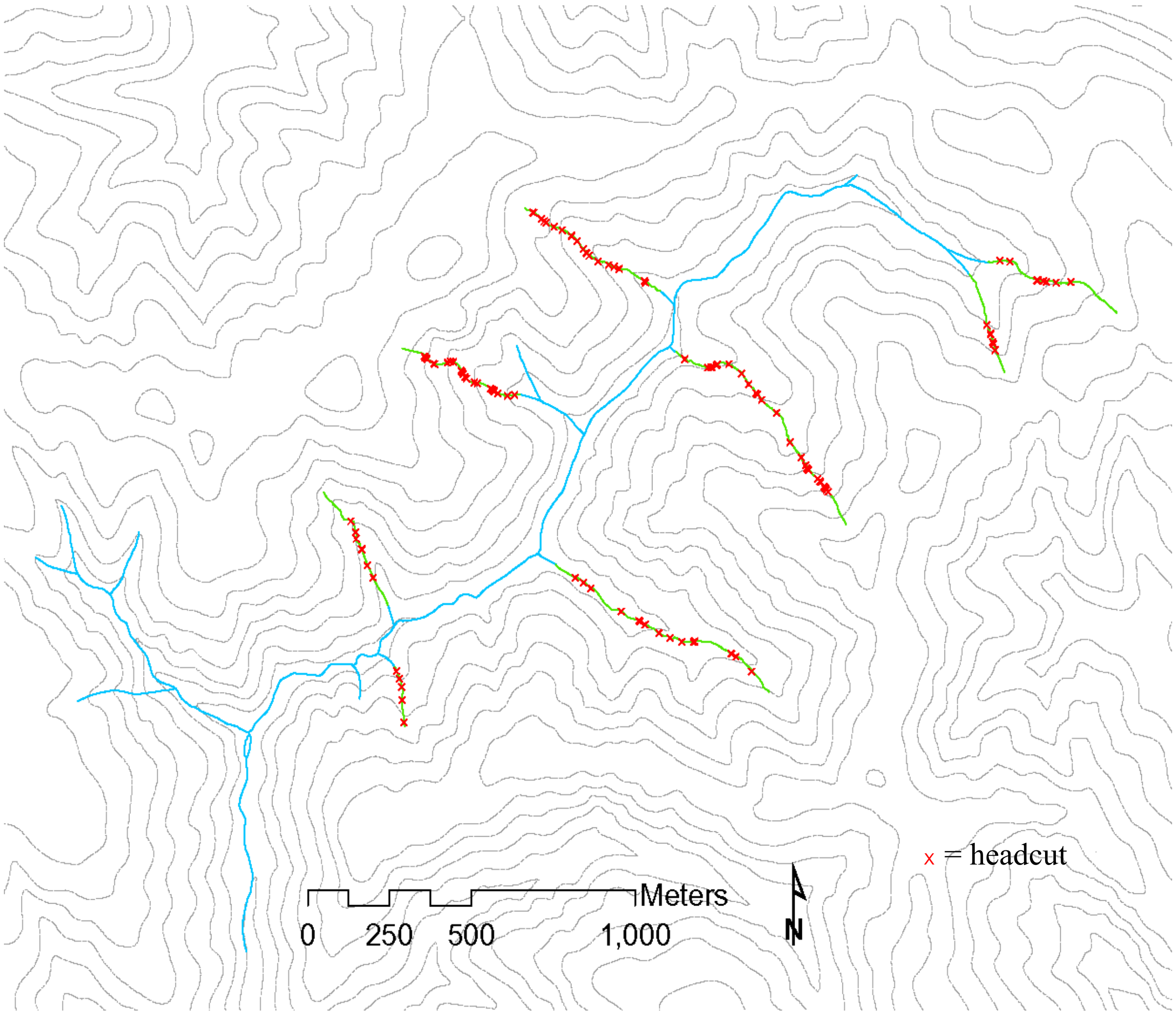

Figure 16a. Location of headcuts taller than 0.7 m in the North Fork of Caspar Creek.

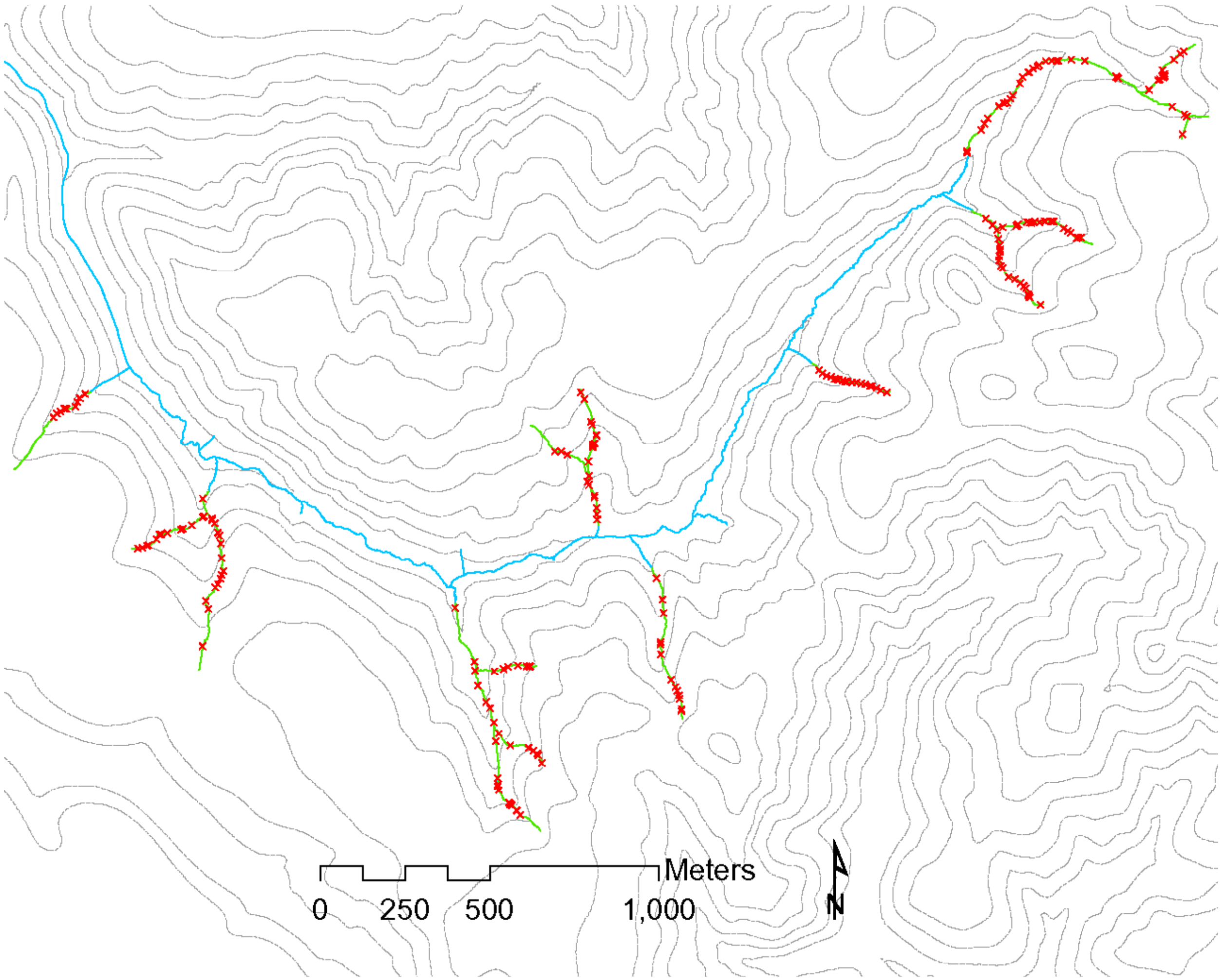

Figure 16b. Location of headcuts taller 0.7 m in the South Fork of Caspar Creek.

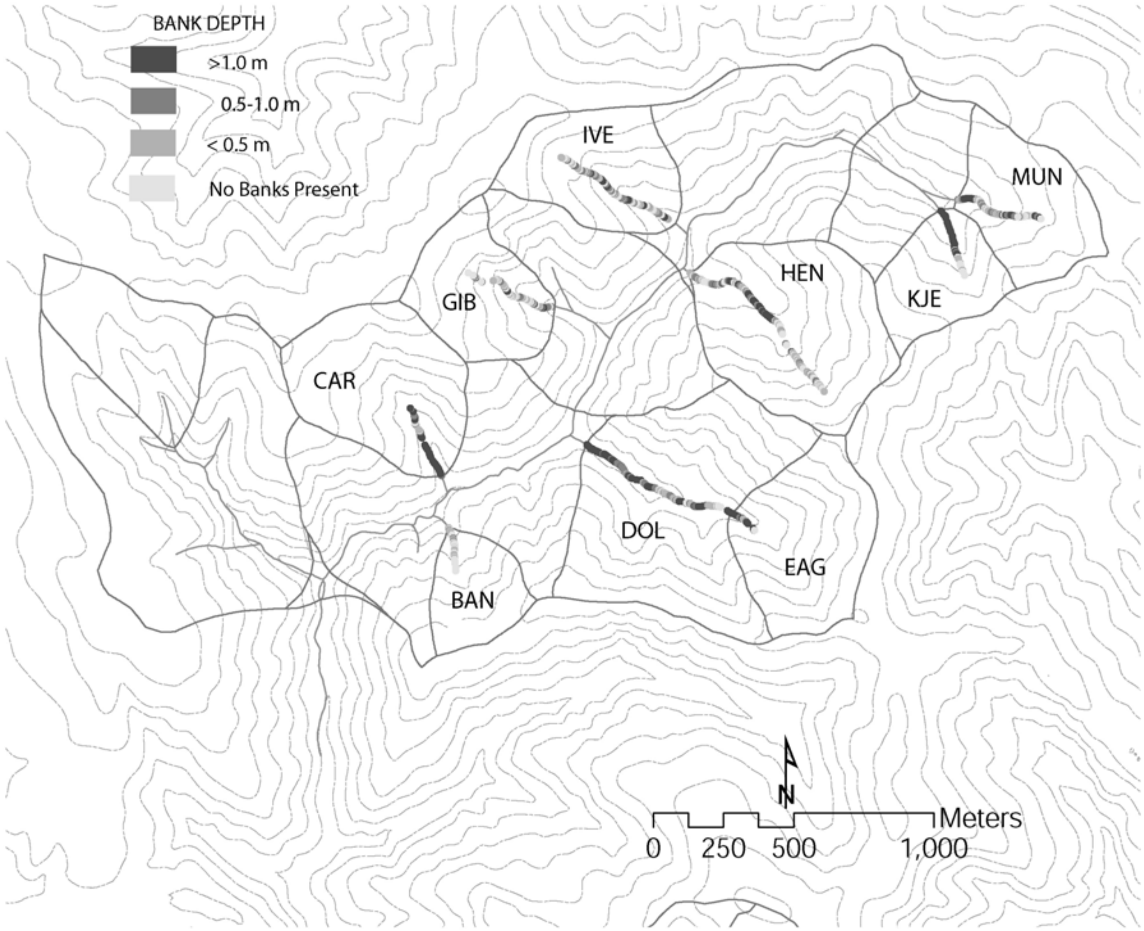

Figure 17a. Channel depth measurements in tributaries to the North Fork of Caspar Creek.

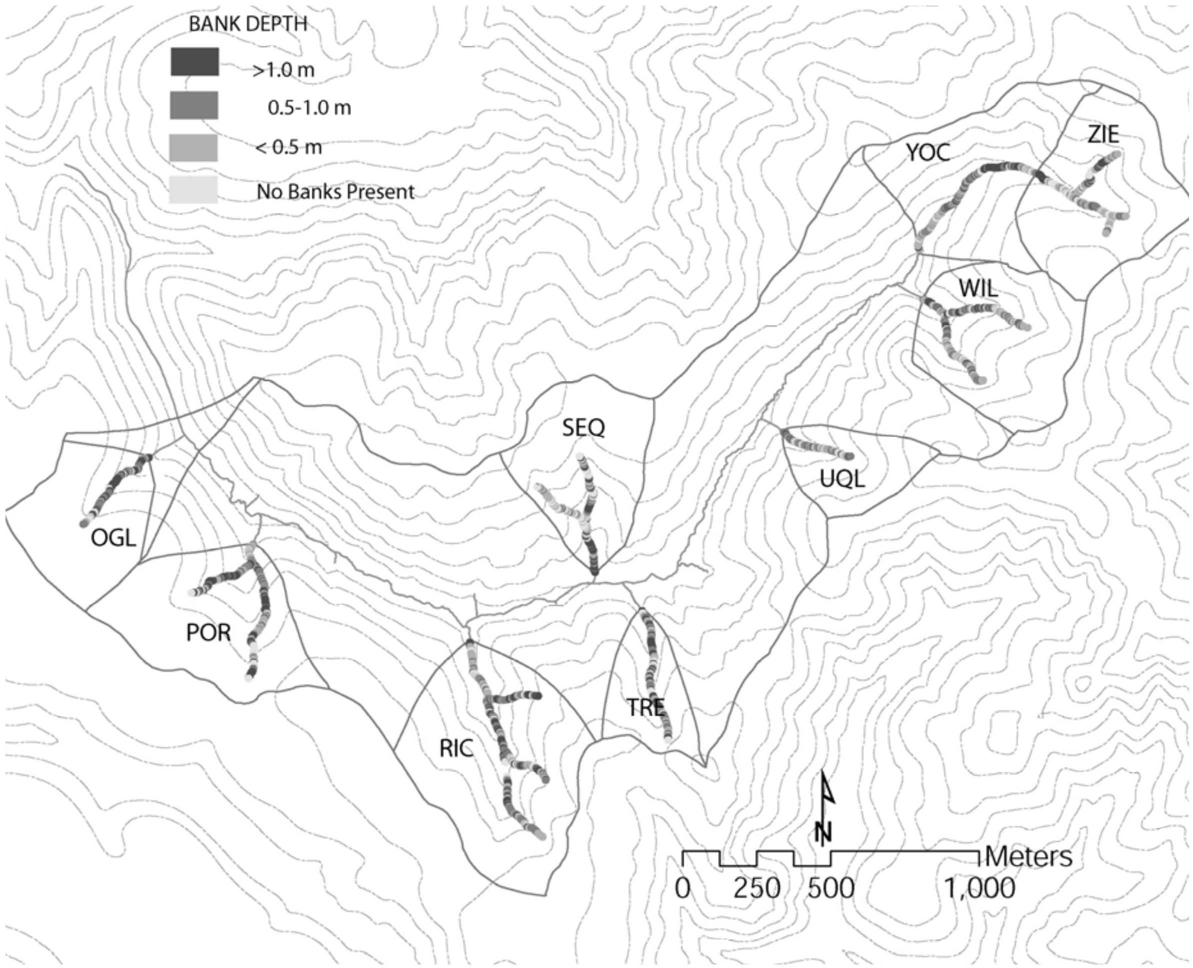

Figure 17b. Channel depth measurements in the South Fork of Caspar Creek.

Table 3. Summary of channel and gully measurements in each tributary.

Tributary subwatershed	Area of basin (ha)	Length of Channel Surveyed (m)	Measured Volume of Gully (m^3)	Measured bank area (m^2)	Headcuts observed at least 0.7 m tall
BAN	10	164	83	138	6
CAR	27	287	817	906	9
DOL	77	739	2005	1936	25
EAG	27	160	425	461	4
GIB	20	363	464	546	29
HEN	39	697	909	1035	41
IVE	21	502	731	784	27
KJE	15	253	1686	1087	7
MUN	16	347	574	517	13
OGI	18	350	477	643	13
POR	32	780	1563	1401	34
RIC	49	1144	1803	1829	48
SEQ	17	668	1120	1001	27
TRE	14	489	632	838	24
UQL	13	269	335	390	31
WIL	26	699	891	1064	59
YOC	53	1269	1486	1785	57
ZIE	25	694	621	859	26

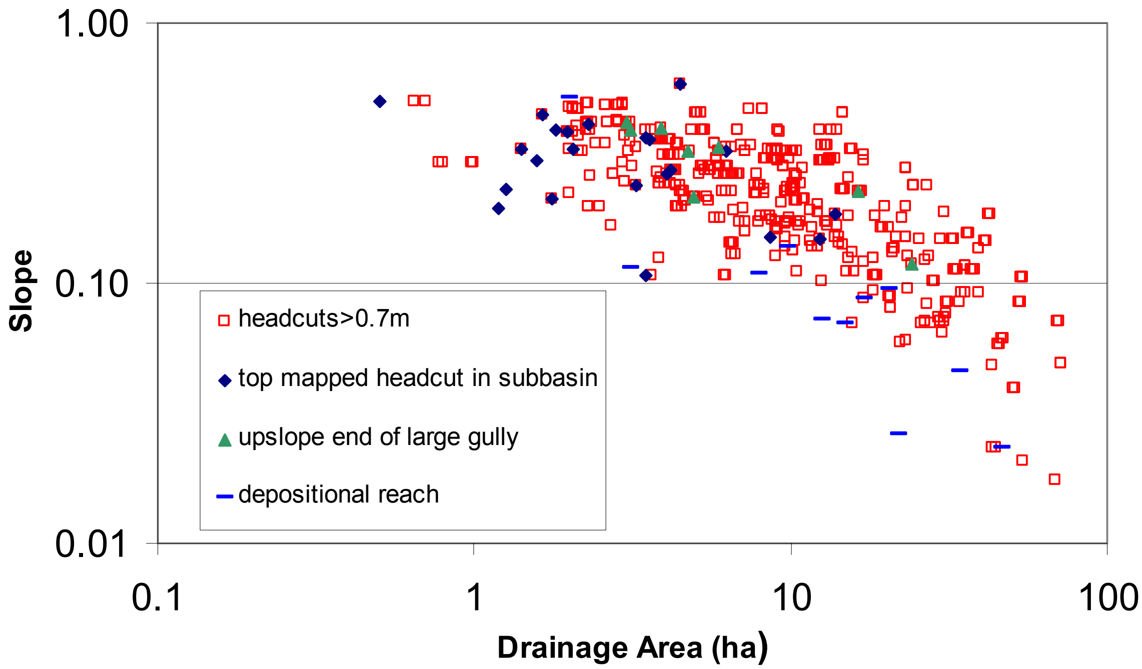

Figure 18. Slope and drainage area at all headcuts greater than 0.7 m, at the upstream-most mapped headcut in each subwatershed, at headcuts defining the upslope end of large gullies, and at major depositional reaches.

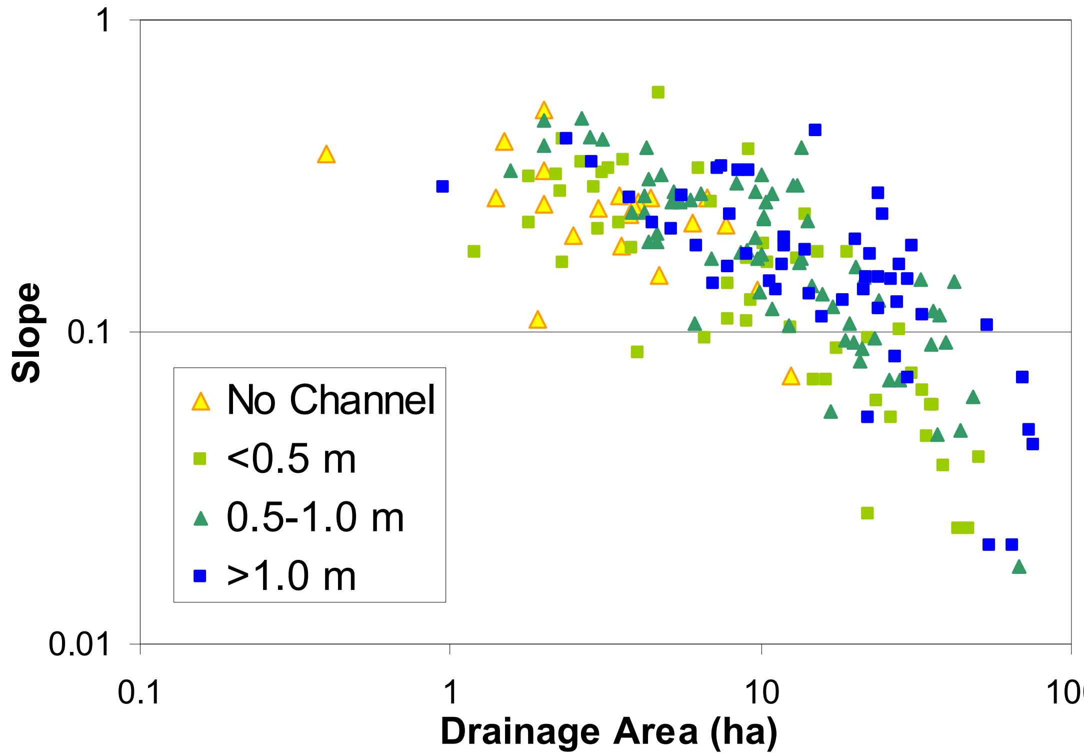

Figure 19. Channel depth compared with slope and drainage area. Channels were sampled at 50-m intervals.

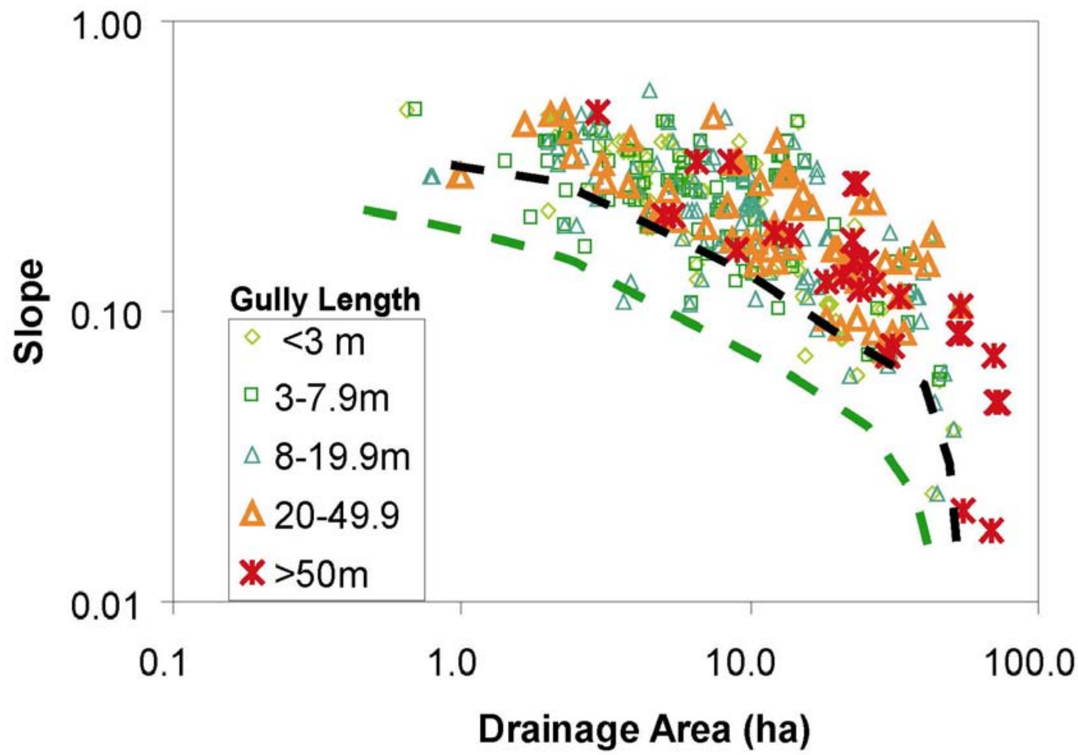

Figure 20. Channel slope and watershed area data for gullies of different lengths. Note that the threshold for gullies exceeding 20 m in length (black dashed line) is different than the threshold for occurrence of short gullies (green dashed line). Multiple headcuts may occur within gullies if downstream headcut lips are entrenched within banks at least 0.5 m deep.

Surveys of Headcut and Bank Erosion

Headcut Retreat

Headcut retreat summary. Headcuts were observed to either erode rapidly (>1m yr^{-1}), erode gradually (2 to 15 cm yr^{-1}), or not erode noticeably at all (Table 4). Of fifty-two monitored headcuts, three migrated rapidly during the four-year study period, within the last two years of the period in all three cases. Of these fifty-two, eleven headcuts were surveyed with enough resolution to detect slower movements, while the others were not resurveyed and motion was only noted if it was rapid enough to detect visually. Of the eleven headcuts surveyed at a higher resolution to detect slower movements, four moved at a measurable rate of 2-15 cm yr^{-1} (including two of the headcuts that moved rapidly, when they were not retreating rapidly), three others appeared to have retreated slightly based on debris accumulations at their base, and five showed no sign of motion.

Specific headcut observations. The most rapid observed headcut retreat occurred along a reach 100 to 200 meters downstream of the ZIE stream gage in subwatershed YOC. Headcuts YOC 18 and YOC 20 were observed to fail in the winters of 2003 and 2004, after the initial resurvey of the headcuts was completed.

Figure 21 illustrates YOC 18, which retreated about 30 cm along part of its face between 2000 and 2002. The change observed between 2000 and 2002 was most

Table 4. Summary of headcut change observations.

Headcut	Observations
YOC 18	Parts of left face retreated up to 30 cm, most of face unchanged between 2000 and 2002. Trees on right bank were undercut in 2004.
YOC 20	Approximately 30 cm retreat between 2000 and 2002, another 1.8 m in winter 2003, and approximately another meter by February 2004, for a total retreat of approximately 3 meters over 4 years. Overhung face was present prior to failure of undercut root structured roof in 2003, after which vertical headcut face moved upstream, preserving vertical shape.
ZIE 24	Approximately 5-10 cm retreat between 2000 and 2002, confirmed by both face-on survey method and oblique cross-section; visually estimated another 10-15 cm retreat by 2004, for a total retreat of approximately 20-25 cm. This was the only major headcut face surveyed that was not overhung in 2000. Most of headcut lip moved between two small roots during this time.
MUN 9	Survey resolution not adequate to detect change between 2000 and 2002, no visual change detected 2004. Chunks of the face and wall, approximately 1-20 cm thick, appear to be breaking off and accumulating in channel, but survey resolution did not catch the change.
MUN 12	Survey resolution not adequate to detect change between 2000 and 2002, no visual change detected 2004. Chunks of the face appear to be breaking off as in case with MUN 9.
YOC 6	Visually appeared to retreat, and plungepool filled with sediment near apparently retreated face, but a wood lip was not undercut and the oblique cross-section showed no retreat.
ZIE 36, 40	Oblique cross-sections failed to detect headcut retreat in either of these.
ZIE 38	Oblique cross-sections detected 3-8 cm headcut retreat.
MUN 5, 6	Oblique cross-sections of two adjacent headcuts failed to detect retreat, but face was overhung. Plunge-pool of upstream headcut deepened by 30 cm at deepest between 2000 and 2002.
ZIE 50	Not part of higher-resolution survey; this headcut was surveyed in lower resolution than those listed above during the laser theodolite mapping effort in summer 2000. Approx. 2 cubic meters on left bank of headcut collapsed, including survey-pin, in February 2004.

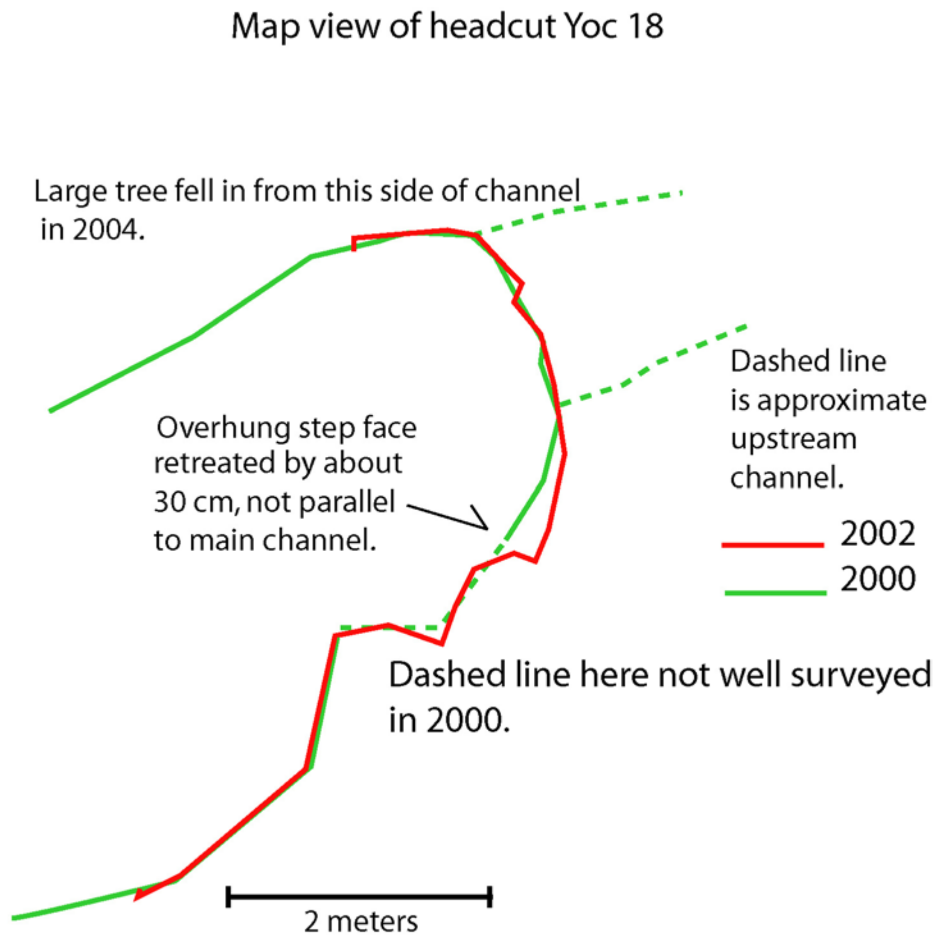

Figure 21. Map of YOC 18. The headcut undercut a live rootwad supporting several mature second-growth redwood trees. The trees fell into the channel from the north bank (top of figure) in December 2003 or January 2004; the headcut has not been resurveyed since this event.

pronounced in a direction slightly to the downstream left of the main in-flowing thalweg. Other parts of the headcut did not retreat measurably over this period. Subsurface pipe flow and seepage were both observed in many different parts of the headcut. Eventually this headcut undercut a clump of mature second-growth redwood trees sprouting out of an old-growth stump on the side of the channel opposite the headcut retreat observed earlier, causing the rootwad and trees to topple into the channel in the winter of 2004 (Figure 22). Note that even though the trees fell in from the right side, roots extended across the channel to the left side above the portion of headcut that was observed to retreat between 2000 and 2002. The headcut was not resurveyed after the tree fell into the channel.

A detailed laser survey showed that YOC 20 (Figure 23) first experienced a small change between 2000 and 2002, retreating at a rate of 15 cm/yr in parts of its face. It then moved dramatically in the winter of 2003, undercutting a root mat and retreating about 1.8 meters. A root mat that had formed the lip from 2000 through 2002 extends over the channel downstream of the new headcut (Figure 24). A field visit during 2004 revealed further retreat of about 1.2 meters, with a spur migrating towards a tributary that enters via a pipe. The rapid retreat occurred only over a narrow portion of the original headcut, leaving a narrow channel path upstream of the old headcut location. The new headcut has maintained an abrupt vertical drop of approximately 2 meters as it migrates upstream, showing no sign of diffusing.

YOC 20 provides an example of a resistant root lip apparently influencing the rate of headcut migration. In the two years after undercutting the root lip, the headcut

Figure 22. Headcut YOC 18, which showed little change between the 2000 and 2002 surveys, undercut mature second-growth trees in the winter of 2004. The collapsed area is on the left side of the photo, which was taken looking up-channel.

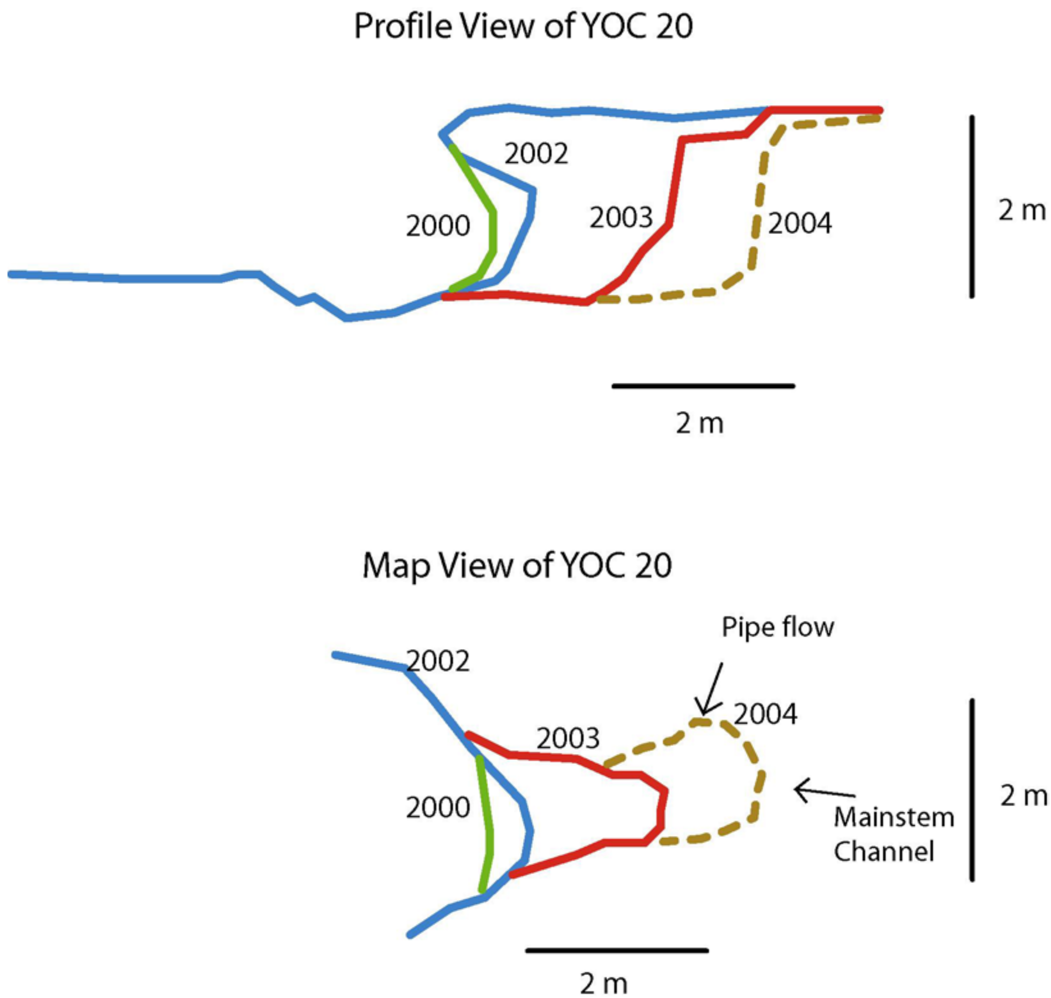

Figure 23. Changes in morphology of headcut YOC 20; this was the largest movement observed. The headcut undercut a root mat at its former lip, and the root mat still hangs over the channel. Currently there is no resistant object at the lip of the headcut.

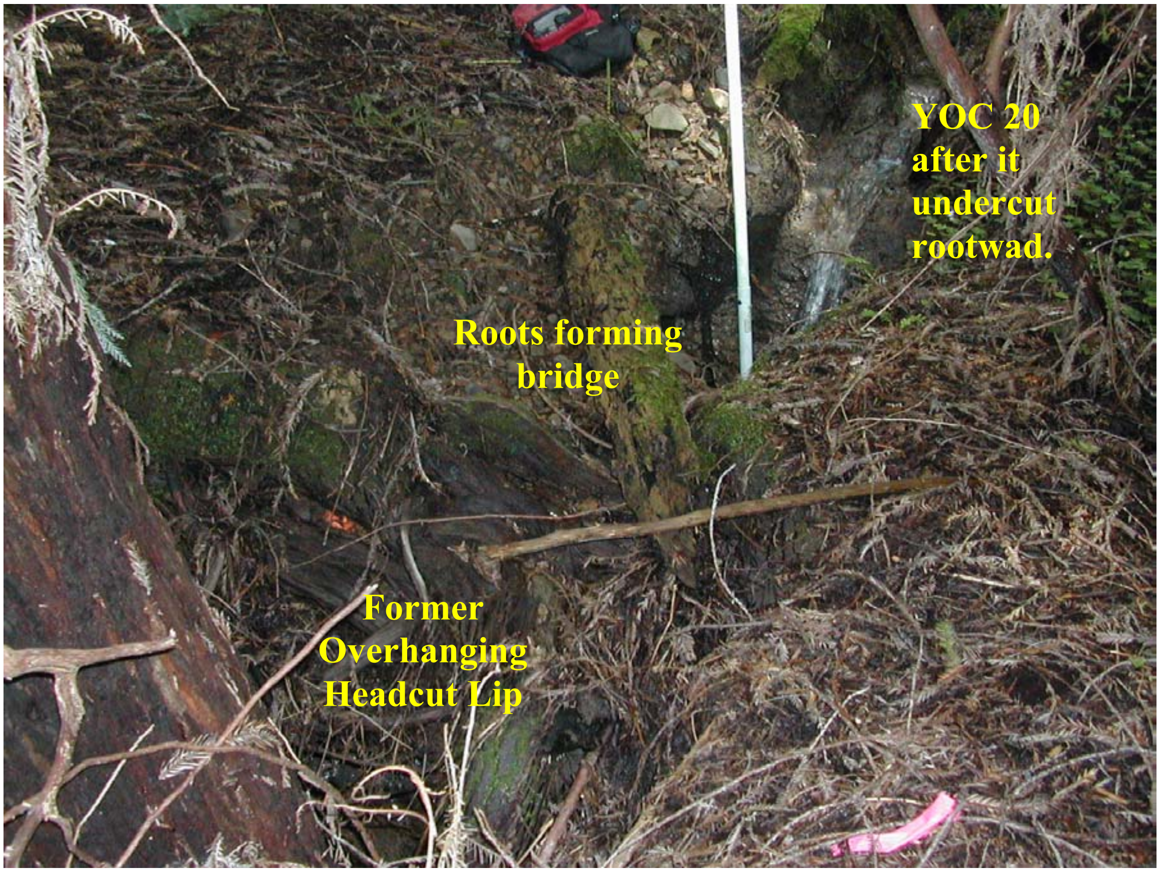

Figure 24. Headcut YOC 20 after it had undercut the rootwad that had formed the former headcut lip. The white survey rod sticks up from the floor of the channel just downstream of the headcut. The former headcut position is in the foreground, in front of roots now forming a bridge over the channel.

migrated about ten times faster than previously. Scouring of the armor layer immediately upstream of the current headcut location has occurred along the upstream thalweg, now that the root is no longer acting as a grade-control structure. Underneath the thin armor layer upstream of the headcut is a cohesive clay-rich layer featuring gleyed clays that apparently had been under the water table in the past, but now are more than a meter above the current winter water surface.

The other headcut that obviously failed was ZIE 50. The initial survey was brief here as part of the 40-headcut low-resolution survey: the thalweg was mapped with a theodolite and the position of the headcut noted. A failure of one wall of the headcut pulled a survey pin into the channel, along with about two cubic meters of soil. This failure appears to have been more of a mass failure than stream-flow-induced headcut retreat, as the direction of failure was towards the bank adjacent to the headcut rather than up the channel.

Headcut ZIE 24 marks the head of the sizable gully upstream of ZIE station; two smaller gullies, which parallel each other along the valley floor, spill into the larger gully at this headcut. ZIE 24 is the only headcut surveyed in detail that did not feature an overhung root lip obscuring the face from top-down measurements, allowing both tapeline and laser surveys to be used. Between 5 and 10 cm of retreat was detected between 2000 and 2002. Observation of the position of the headcut relative to undercut tree roots just downstream of the lip suggest that an additional 10 to 15 cm of retreat occurred between July 2002 and January of 2004.

Resurvey of the MUN 9 and MUN 12 headcuts showed little evidence of change. The fresh faces of MUN 9 and 12 and the soil pedons accumulating in the channel at the bases of both headcuts suggest that some headcut retreat had occurred, but the amount could not be quantified. Material exposed in the lower part of the face of these headcuts appears to be saprolite overlain by alluvium that was saturated for sufficient time to accumulate gleyed clay deposits prior to lowering of the water table by incision. There is a smaller headcut just downstream of MUN 12, but no motion was detected on either the main headcut or the subsidiary headcut. Despite the lack of observable motion, the headcut of MUN 12 appears far from stable, with a vertical face of erodible material and a slightly overhung lip at a tree root (Figure 25). The face of MUN 9 is similar, but is more deeply overhung under a structure partly held together by roots from an old-growth stump.

Sediment that appeared to have fallen from the headcut face of YOC 6 had built up at the base of the headcut, but the tapeline did not detect the retreat because of an accumulation of wood over the headcut lip. A tapeline survey of ZIE 38 showed 3 to 8 cm of retreat along two separate faces of a compound headcut. Headcuts MUN 5 and 6 did not exhibit headcut face retreat, but the plunge pool between the headcuts deepened by 30 cm at its deepest part. No motion was detected at ZIE 36 or ZIE 40. ZIE 30 was initially surveyed but was not resurveyed, as it was part of an inactive reach of channel that was partially filled with accumulated duff. There was no visible evidence of retreat at the wood-lipped headcut.

Figure 25. View upstream at headcut MUN 12. The drop from lip to plungepool is about 2 meters. Note wood at lip and the hanging root mat.

Summarizing the above data, headcut erosion rates can be thought of as bimodal. Many headcuts erode at rates of less than 15 cm yr^{-1}, while some eroded at rates in excess of 1 m yr^{-1}, and there were no intermediate cases. This difference in retreat styles probably reflects differences in erosion mechanisms: gradual retreat occurs by spalling of face materials, while rapid retreat may occur primarily by cantilever failure as a headcut is undercut by plungepool erosion or sapping of materials near the base of the headcut within active channels. Retreat is likely to be most rapid after the lip of a headcut has been undermined when there is no resistant wood, root, or rock element immediately upstream to buttress the headcut.

Average Rate of Headcut Retreat. Estimation of an average rate has to take into account that two different resolutions of measurement were applied: rapid rates of retreat were detectible if they occurred on any of 52 headcuts, while only 11 headcuts were surveyed closely enough to estimate the more gradual style of retreat. If three of fifty-two headcuts retreated rapidly over four years for a total distance of 5 m (3 m at YOC 20, 1 m at YOC 18, and 1 m at ZIE 50), we can estimate a total retreat of 1.25 m yr^{-1} distributed over 52 headcuts, or a rate of 2.2 cm yr^{-1} per headcut from rapid retreat. This rate is probably highly variable between years. Gradual headcut erosion observed at the 11 resurveyed headcuts averaged 4 cm yr^{-1}. The 4 cm yr^{-1} figure is obtained by averaging retreat rates from resurveyed headcuts that either moved gradually or not at all, and from the periods of gradual motion for the two of these 11 headcuts that later moved rapidly. Summing rates of rapid and gradual retreat produces an estimated average headcut retreat rate of about 6 cm yr^{-1} for the study period. This calculation employs two questionable assumptions: 1) The 52 headcuts observed from 2000-2004 are representative of the frequency and rates of more rapid headcut retreat, and 2) The 11 headcuts measured closely enough to detect gradual retreat are representative of rates and frequency of more gradual retreat. The average of 6 cm yr^{-1} should be thought of as a rough estimate.

Bank Retreat

Like headcuts, banks can retreat gradually or fail suddenly. In 2000 and 2002, channel cross sections were surveyed upstream and downstream of the headcuts in MUN, YOC, and ZIE that were monitored using the oblique tapeline method. Bank retreat was calculated as the average of retreat at the top and bottom of the banks. Results from the 12 cross-sections showed that banks retreated on 12 of the 22 measurable banks (two banks were overhung and retreat was not measured) at an average rate of 1.8 cm/yr (Table 5). This sample is not necessarily representative; half of the banks observed were downstream of headcuts. Measurable retreat was noted both upstream and downstream of the headcuts (Figure 12). As was the case with headcut retreat, bank erosion measurements indicated that some banks eroded rapidly (up to 10 cm/yr), some slowly (0.25-2 cm/yr) and almost half of the banks observed showed no movement.

Mechanisms for bank retreat include active undercutting at the base of the bank, collapse, or spalling of the surface layer. Channels either widened over the study period or showed no change; no channels were observed to narrow due to soil creep. In some

Table 5. Measurements of Bank Retreat (cm) between 2000 and 2002. Average measured bank retreat over 2 years is 3.51 cm (1.75 cm yr^{-1}) at the non-undercut sites.

Location	Left Bank	Right Bank	Total Widening
YOC 6 downstream	0	1.5	1.5
YOC 6 upstream	1	1.5	2.5
ZIE 24 downstream	12	8	20
ZIE 24 upstream	20.5	0	20.5
ZIE 36 downstream	overhung[1]	0	na
ZIE 36 upstream	0	0	0
ZIE 38 upstream	0	5	5
ZIE 38 downstream	0	0	0
ZIE 40 upstream	4	5	9
ZIE 40 downstream	10	3	13
MUN 5 downstream	overhung	0	na
MUN 6 downstream (upstream of MUN 5)	0	5	5

[1] Banks noted as “overhung” may have eroded, but the overhanging bank lip did not recede.

cases bank retreat occurs by failures that are visible to a casual observer, but in most places bank retreat is subtle but can be detected by cross-section resurvey.

Importance of Gullies as Sediment Sources

Overview of Approaches and Results

Five approaches are used to assess the importance of gullies as sediment sources in Caspar Creek. The approaches have similarities, but are different enough that each will be considered independently.

1) Topology of Gaging Station Data: Sediment production from gullies is assessed by comparing the production of sediment between two nested stream gages. If sediment production per unit area increases downstream, without obvious hillslope sources, the additional sediment could have been produced from in-channel sources.
2) Bank and Headcut Sediment Production: Short-term sediment production rates from bank and headcut surveys is compared to sediment production measured at stream gages.
3) Long-term Average Gully Sediment Production: Long-term sediment production is estimated from gully volume and age and compared to recent sediment output at stream gages.
4) Examination of Hillslope Sediment Production Data: Hillslope sediment production is compared to sediment output in different watersheds.

5) Correlation of Gully Dimensions With Sediment Output: Correlation between the degree of gullying in subwatersheds and sediment output at the gaging stations is examined.

These approaches are each described in the following sections.

Approach 1: Topology of Gaging Station Data

Overview. Two pairs of subwatersheds that were mapped for gullying are nested: DOL and EAG in the North Fork, and YOC and ZIE in the South Fork. These gage pairs provide comparisons of sediment production between downstream and upstream portions of a watershed. Differences in unit-area sediment production can indicate relative sediment input from hillslopes and gully erosion. In general, downstream channels would be expected to have hillslope sediment inputs of lesser magnitude than upstream channels, which are expected to be more tightly coupled with hillslopes because they lack floodplains and terraces. An increase in unit-area sediment production downstream could come primarily from gully erosion or other in-channel sources.

Gages DOL and EAG. Gage DOL lies downstream of gage EAG. The basin above EAG has more hillslope-channel interaction than DOL and was logged in 1991; the basin area downstream to DOL has not been logged since the first entry. In the lower watershed, valley-fill deposits isolate much of the channel from hillslope inputs. Flow and sediment records show that annual suspended sediment yield per unit area from DOL has equaled or exceeded that from EAG in most years (Table 2, Figures 3 and 26). Sediment yield increased in DOL during the first two winters following logging in the

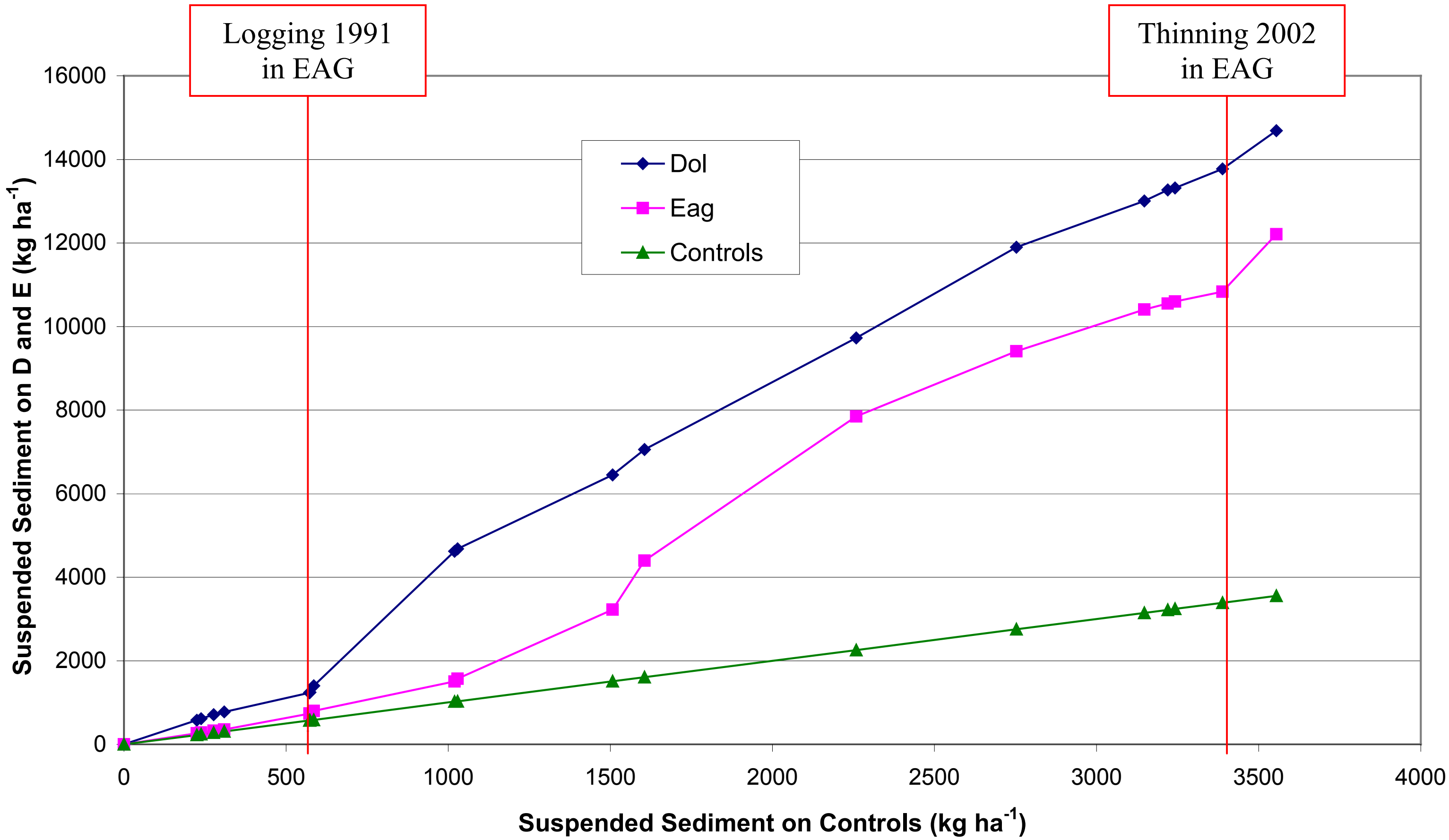

Figure 26. Cumulative suspended sediment measured at gages DOL and EAG. Each segment between markers represents a year of suspended sediment production between 1986 and 2003.

basin, but an increase in EAG was delayed until the third winter. No landslides were noted within the DOL watershed during this period that could have explained the sediment pulse. Since DOL features deeply gullied channels that are generally isolated from hillslope sediment sources by valley-fill terraces, much of the sediment entering the stream between the EAG and DOL gages is likely to originate in or adjacent to the channel. Several small tributaries do feed into DOL but these would have been unaffected by logging. The increase in sediment yield in DOL during the two years following logging without additional sediment inputs from EAG was likely caused by logging-related increases in flow that increased gully erosion between EAG and DOL. This pattern suggests that the initial impact of the logging was the runoff increase rather than the delivery of sediment from the EAG hillslopes to the channel. When interpreting these data, consider that the DOL basin (77 ha) is about three times larger than the EAG basin (27 ha), so that for those water years in which DOL exported about three times as much sediment per unit area as EAG (1992, 1993) it exported about nine times as much total sediment as it received from EAG.

Gages YOC and ZIE. Tributary ZIE of the South Fork is upstream and nested within the watershed of tributary YOC. Over the time period observed, YOC produced approximately two to four times as much sediment per unit area during each storm (Figure 27), or about four to eight times as much total sediment. This pattern suggests that significant sediment is generated between stations YOC and ZIE. One source of this sediment could be the large gullies that form much of the mainstem channel in YOC. As

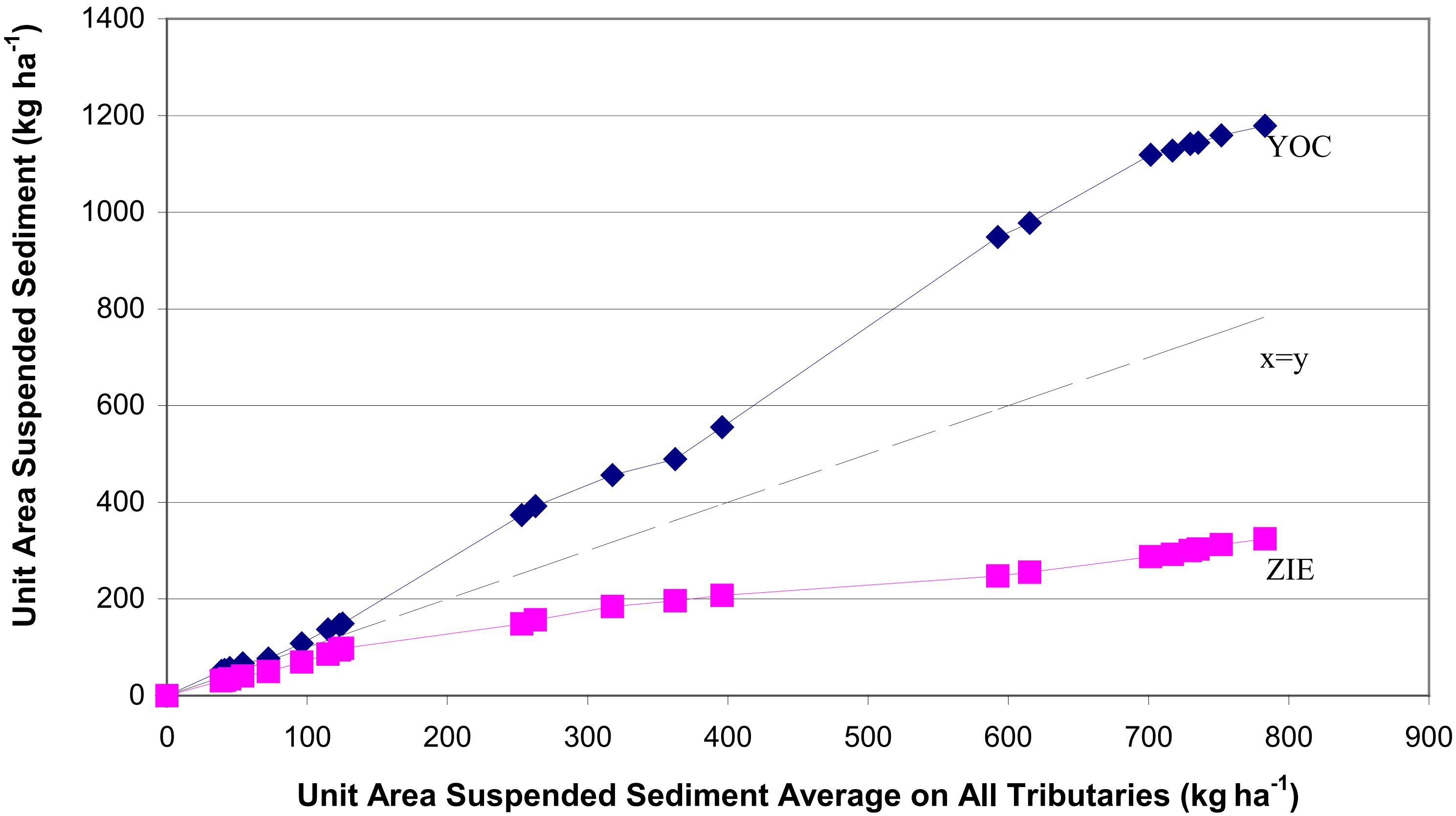

Figure 27. Cumulative sediment production per unit area on YOC and ZIE from 2001-2003 (based on the 22 events which exceeded the storm definition threshold). Note that since YOC has about twice the drainage area as ZIE, the absolute difference in suspended sediment exported is even greater.

will be explored in the next section, these gullies could produce significant sediment. The lower portion of YOC is well shielded from direct hillslope inputs by valley flats, although between headcuts YOC 7 and YOC 18 the channel cuts an inner gorge, directly destabilizing the hillside. Gully-related destabilization is particularly notable along the 160 m of channel between headcuts YOC 12 and YOC 18, although no failure of noticeable size occurred on these slopes during three years of observation. It is likely that surface erosion and small slides from slopes destabilized by the gullies contribute some sediment along this reach.

Several small tributaries enter YOC downstream of the ZIE station, with the largest entering on the north side of the channel near headcut YOC 20. This tributary has only one-fifth the source area of ZIE and is scoured to bedrock in many places. Where it intersects the YOC valley floor it aggrades, with flow filtering through valley gravels before joining the main channel. The smaller tributary channels also form aggrading fans on the mainstem valley floor. Given the depositional zones between the tributary watersheds and the mainstem channel, it is unlikely that the tributaries could account for much of the four-fold increase in sediment load in YOC downstream of ZIE. The large gullies along the valley axis, in combination with inputs from undercut inner gorge slopes destabilized by the gullies, are the apparent sources for the disproportionate sediment inputs between the ZIE and YOC gages. Depositional reaches upstream of the lowest large ZIE gully, which cut the gage off from most of the gullies farther upstream, also contribute to its low sediment output per unit area.

Approach 2: Bank and Headcut Sediment Production

Case Study: YOC and ZIE. The bank and headcut resurveys were carried out in channels YOC, ZIE, and MUN between 2000 and 2002. YOC and ZIE, with their nested gages, are an ideal case study for comparison of sediment production with measurements of bank and headcut erosion. We can compare gully erosion rates estimated over the two years of observation along the YOC channel to sediment output measured at the gages over the same period. Suspended sediment yield from YOC gage averaged 224 kg $ha^{-1}yr^{-1}$ in water years 2001 and 2002. Given 53 ha as the area of YOC and assuming a bulk sediment density in the range of 1185 to 1500 kg m^{-3}, the volume of exported sediment was 7.9 to 10.0 m^3yr^{-1}. Substituting values for tributary ZIE, only 1.3 to1.6 m^3yr^{-1} of that total is accounted for at the ZIE gage, leaving 6.6 to 8.4 m^3yr^{-1} originating from the reach between ZIE and YOC.

As observed in the last section, depositional reaches partially disconnect sediment transport to the lower reaches of ZIE from gullies upstream. In contrast, deposition within and adjacent to the mainstem YOC channel downstream of the ZIE station is not considered great enough to disrupt the bulk of suspended sediment transport.

Between stations ZIE and YOC, approximately 1100 m^2 of bank area and 60 m^2 of headcut area are directly connected with the channel network. We can assume that headcuts recede more quickly than banks for channels to maintain lengthy reaches of low width-to-depth ratio downstream of migrating headcuts, and this assumption is supported by headcut survey data. However, it is difficult to estimate an average headcut retreat rate because of the short monitoring period and the high variance among monitored headcuts;

headcuts move at different rates depending on variables including flow and the location of resistant objects. At the estimated headcut retreat rate of 6 cm yr^{-1} and bank retreat rate of 1.8 cm yr^{-1}, headcut and bank retreat together would generate 23.4 m^3 of sediment per year, more than twice the 7.9 m^3 yr^{-1}exported from YOC during these two years.

Above ZIE, a depositional area appears to disconnect the lower channel from upstream reaches. This is a more substantial cutoff than the minor depositional reaches observed along the mainstem downstream of station ZIE. If one assumes that all upstream sediment is deposited in the depositional reach and again applies the rates of 6 cm yr^{-1} for headcut retreat and 1.8 cm yr^{-1} for bank retreat, the large gully immediately upstream of the gage would generate approximately 3.2 m^3 yr^{-1} of sediment, again more than twice the 1.3 to 1.6 m^3 yr^{-1} of suspended sediment that was observed at the gage. If one instead assumes that all gullies observed upstream of ZIE are able to route sediment through the depositional reach, the amount of sediment generated is even higher.

The unmeasured bedload fraction would explain part of the discrepancy between estimated sediment production and suspended sediment yield. However, if sediment yield is increased to account for the 25-27% of the total load expected to represent bedload transport, the total load calculated for ZIE still falls short of the estimated rate of in-channel sediment production. We can conclude from these calculations that gullies are likely to produce significant sediment, and also that sediment storage occurs within the subwatershed in the short-term.

A significant amount of sediment also likely enters the channel from the hillslopes destabilized by gullying between YOC 12 and YOC 18, and monitoring this source would allow refinement of the sediment input estimates. Headcut erosion can also accelerate bank erosion. However, bank retreat seems likely to account for a significant amount of sediment.

Extending Short-Term Sediment Production Estimates to Other Watersheds. The above example considered the period of time over which banks and headcuts were measured on the YOC-ZIE reaches. If we extend those calculations to include all tributaries and extend our time period to include gage records for 2003, when rates of sediment production were generally high, we can calculate bank retreat rates needed to generate the volume of sediment transport measured at the gages for the three-year period. Alternative calculations are based on assumptions that major depositional areas trap (1) all, or (2) none of the sediment supplied to them (Figure 28). Using the first assumption, bank retreat rates are computed only for reaches below the downstream-most depositional zone; for the latter assumption, rates are computed for the entire length of gullied channel. Results using both assumptions show that the measured average rate of gully bank erosion for 2001-2002 (1.8 cm/yr) exceeds sediment output for the time period in 10 of 14 subwatersheds. For the remaining four watersheds, gully erosion under assumption #2 exceeds sediment output in all but one case.

This calculation indicates that the estimated bank retreat rate exceeds the value required to explain sediment exported from all watersheds, if storage in valley flats or short-term channel storage is not accounted for. Bank sediment generated downstream of major depositional reaches also exceeds sediment exported from watersheds in most

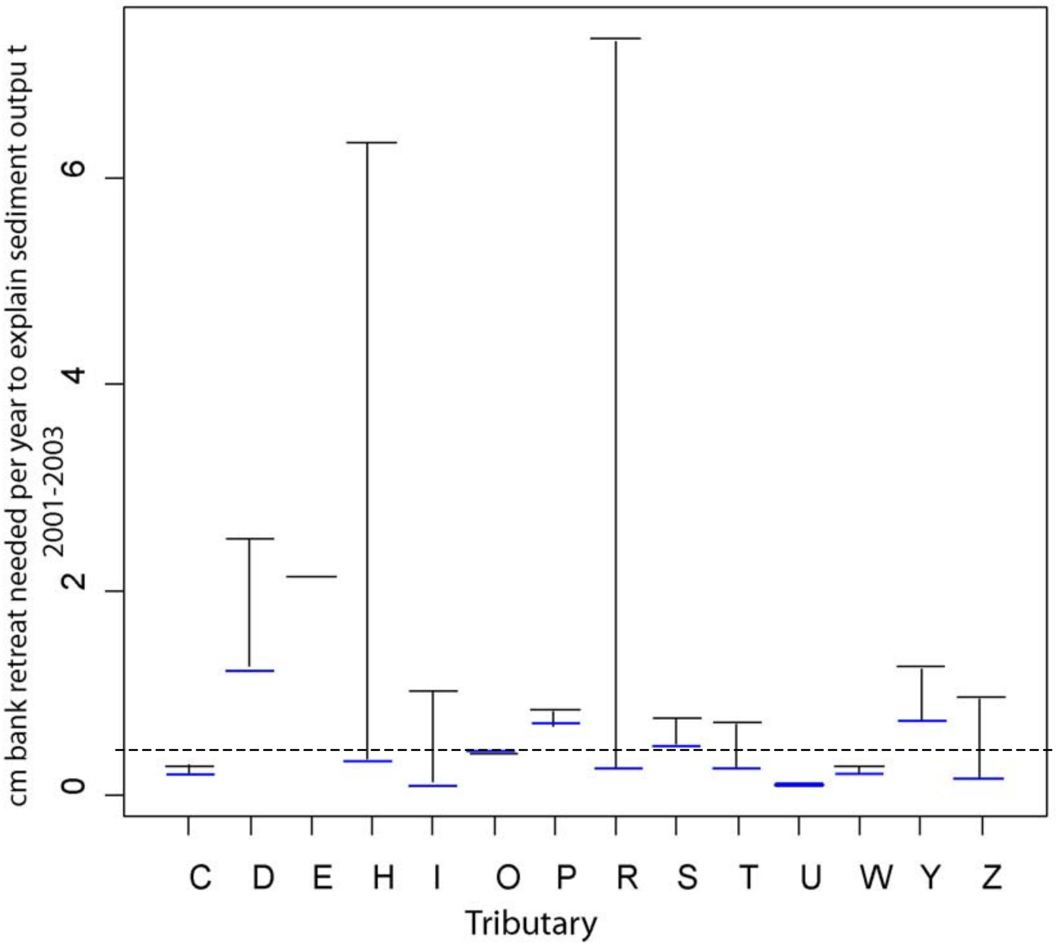

Figure 28. Rates of bank retreat needed to explain sediment exported from different tributaries. The high values represent bank retreat rates needed if only reaches downstream of significant depositional areas are included. The low values represent the rates needed if all mapped banks contribute to downstream sediment loads. Some tributaries (R, H) have large depositional reaches low in the watershed, leading to very different values depending on which assumption is used. Other tributaries (E, U) did not have a significant depositional reach along the mapped portion of the channel.

cases where these depositional reaches are assumed to trap all incoming sediment. The reality is that sediment storage efficiency falls between these two extremes. Storage reaches, including more subtle storage reaches than the ones identified as major, most likely trap a portion of the sediment produced by the gullies and route the rest of the sediment through. Periods of rapid headcut migration would also cause channels to export more sediment than this simple model suggests.

Approach 3: Long-term Average Gully Sediment Production

Long-term rates of gully sediment production can be estimated by dividing the volume of the gullies by their estimated approximate age of 120 years (the time since the midpoint of the dates of initial logging). To achieve their current volume, most of the gullies would have produced sediment over the last 120 years at an average rate that would equal or exceed the average annual suspended sediment yields measured recently. This is true whether one compares volume with sediment rates from 2001-2003 or from 1985-1995 (Figure 29).

The estimated long-term rates calculated here are overall average rates that must have been exceeded during portions of the gullies' development, suggesting that gullies would have to have been more important sediment contributors at times in the past. Sediment production rates are likely to have been greater during earlier stages of gully formation. Even if gullies have slowed down somewhat over their lifetimes, most headcuts are well downstream from the active channel head and most are downstream of other gullies, suggesting that most of the currently active headcuts are far from stopping

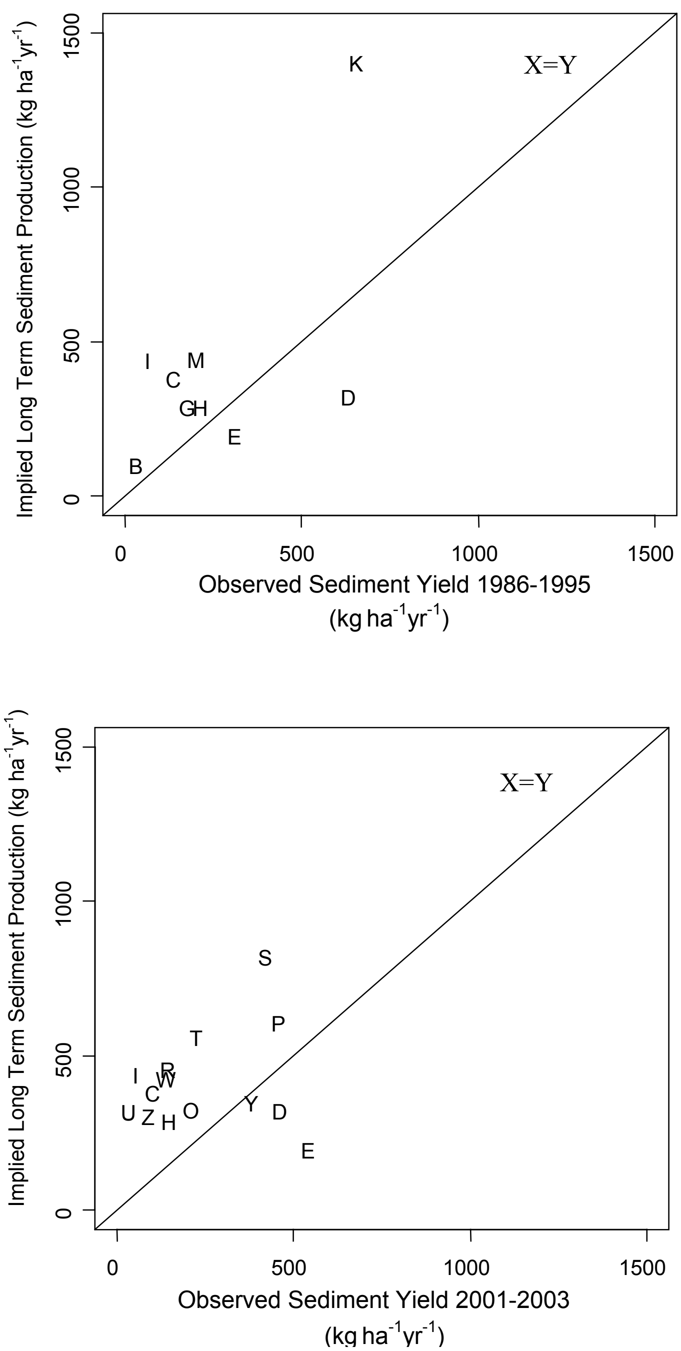

Figure 29. Comparison of rates estimated from gully volumes and ages with observed sediment yields for 1985-1995 (top), and 2001-2003 (bottom).

their migration due to decreased upslope catchment area. The observation that gullies still feature vertical unstable banks and multiple migrating headcuts, even in control watersheds, suggests that active gully erosion does continue 120 years after disturbance. Despite active erosion in the channels, most headcut activity is downstream of headword gully limits established earlier: most of the active headcuts and banks are either downstream of inactive gullies or nested in floors of inactive gullies that also postdate logging.

Approach 4: Examination of Hillslope Sediment Production Data

Landslide and hillslope inputs. Landslides and other hillslope inputs of sediment can account for volumes of sediment exceeding those produced in gullies, yet the distribution of hillslope inputs appears to correlate poorly with that of sediment output. Over 17,000 m^3 of sediment were displaced by landslides in the North Fork of Caspar Creek watershed from 1974 to 2006, as estimated from field measurements of landslides larger than 76 m^3 (Cafferata and Spittler 1998; Keppeler 2006) (Table 6). Assuming a bulk density of about 1185 to 1500 kg/m^3, and dividing over the 33-year period and 473 ha of drainage area, an appropriate value for landslide-generated sediment in the North Fork watershed would be in the range of 1300 to 1650 kg $ha^{-1}yr^{-1}$.

Estimated rates of sediment input from landslides were combined with surface erosion rates estimated by Rice (1996) from erosion plot data to estimate total hillslope sediment displacement in each subwatershed for the period 1986-1995. The mean value for hillslope sediment displacement in subwatersheds of the North Fork is 7,150

Table 6. Slides that exceeded 76 m^3 within North Fork tributaries. The first 11 slides were tabulated by Cafferata and Spittler (1998). The other two are large slides that the author is aware of that occurred since 1998.

Hydrologic Year	Subwatershed	Slide Volume (m^3)
1974	LAN	3306
1986	LAN	1262
1990	GIB	283
1995	XYZ (Z)	3606
1995	ARF	306
1995	GIB	76
1995	CAR	130
1996	EAG	84
1997	HEN	122
1998	LAN	76
1998	HEN	103
2003	GIB	2000
2006	EAG	6000

kg $ha^{-1}yr^{-1}$, a much higher estimate for sediment displacement than that attributed solely to large landslides (> 76 m^3). Rice found that in six of the nine watersheds included in his study, the hillslope erosion rate was well more than ten times the rate at which sediment is exported at stream gages, indicating that most sediment was not delivered to the stream gages. Rice concluded that the delivery ratio is generally low and varies widely between basins, with hillslope sediment displacement being largest in the logged watersheds, which had lower delivery ratios. His data indicate that hillslope sediment estimates are not valid predictors of sediment exported from watersheds (Figure 30), and hence sediment routing and channel processes are important influences on sediment production from watersheds. Sediment yield data shown in Figure 30 do not reflect the likely bedload fraction, equivalent to about 33% of the suspended load (Rice 1996), but even with such a correction, delivery ratios would be small. Increases in sediment output observed in the logged watersheds correlate well with flow increases (Lewis 1998), but not with increases in hillslope erosion.

Impact of a large landslide. Though estimates of sediment displacement rates on hillslopes do not correlate well with suspended sediment output, large landslides can cause a short-term elevation in sediment measured at gages. In January 1995, a slide and debris flow exceeding 3,000 m^3 occurred in subwatershed XYZ on the North Fork (Figure 2). This watershed was ungaged at the time, but a comparison of sediment records from gages upstream (ARF) and downstream (NFC) of the weir pond, which watershed XYZ drains into, showed a pulse in sediment delivery that is discernable for

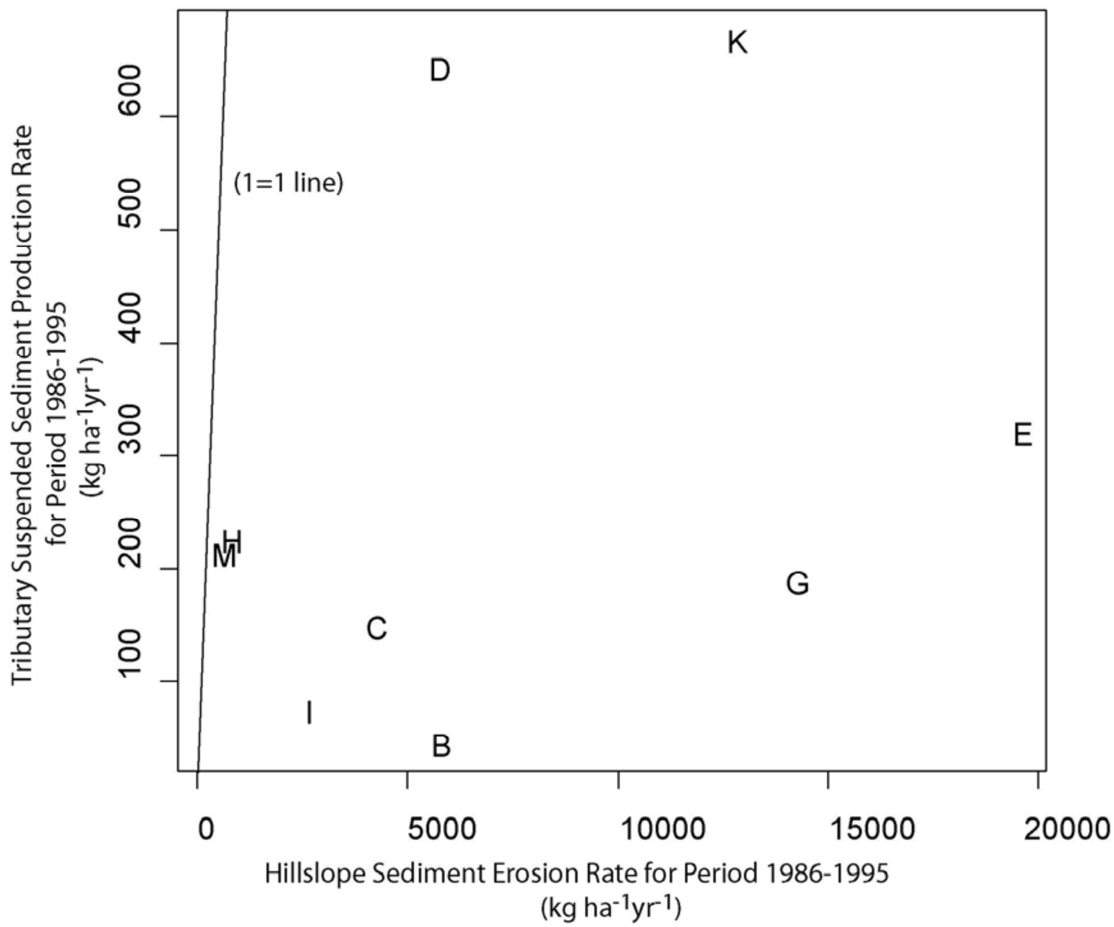

Figure 30. Hillslope erosion (Rice, 1996) fails to predict sediment delivery at stream gages.

the rest of water year 1995. Lewis (1998) describes this landslide as dramatically elevating sediment production at NFC. After 1996, the ratio between annual sediment yields at gage NFC and gage ARF returned to a pattern similar to the pre-landslide pattern (Figure 31). A t-test failed to find a significant difference in ratios between these stations during pre-slide storms and during storms that occurred more than 2 years after the slide ($p=0.88$). A portion of the XYZ watershed had itself been logged in 1985 and 1986. This analysis combines the pre- and post-logging portion of the pre-slide data at ARF. A similar comparison with only the post-logging but pre-slide data also shows no significant difference in ratios.

For the period preceding the slide and for the first six years after it occurred, the only way to evaluate sediment production from the XYZ watershed is by comparing records at the ARF and NFC stations, as above. However, in 2001, six years after the slide, a gage was installed in subwatershed XYZ, downstream of the slide. Since then, the watershed has produced less than the median amount of sediment per unit area from other gages (Table 2) that have not experienced large landslides. The large landslide did not lead to a prolonged increase in sediment delivery. Instead, the bulk of the slide deposit remains in the watershed and is not directly accessed by the channel. Subwatershed XYZ also produces less sediment per unit area than that measured at the nested XRA gage (Figure 2), which was installed upstream of the landslide the year after installation of the XYZ gage. This pattern strengthens the argument that the slide is not the prime driver of sediment export from the watershed 6 to 10 years after the slide. The slide, which

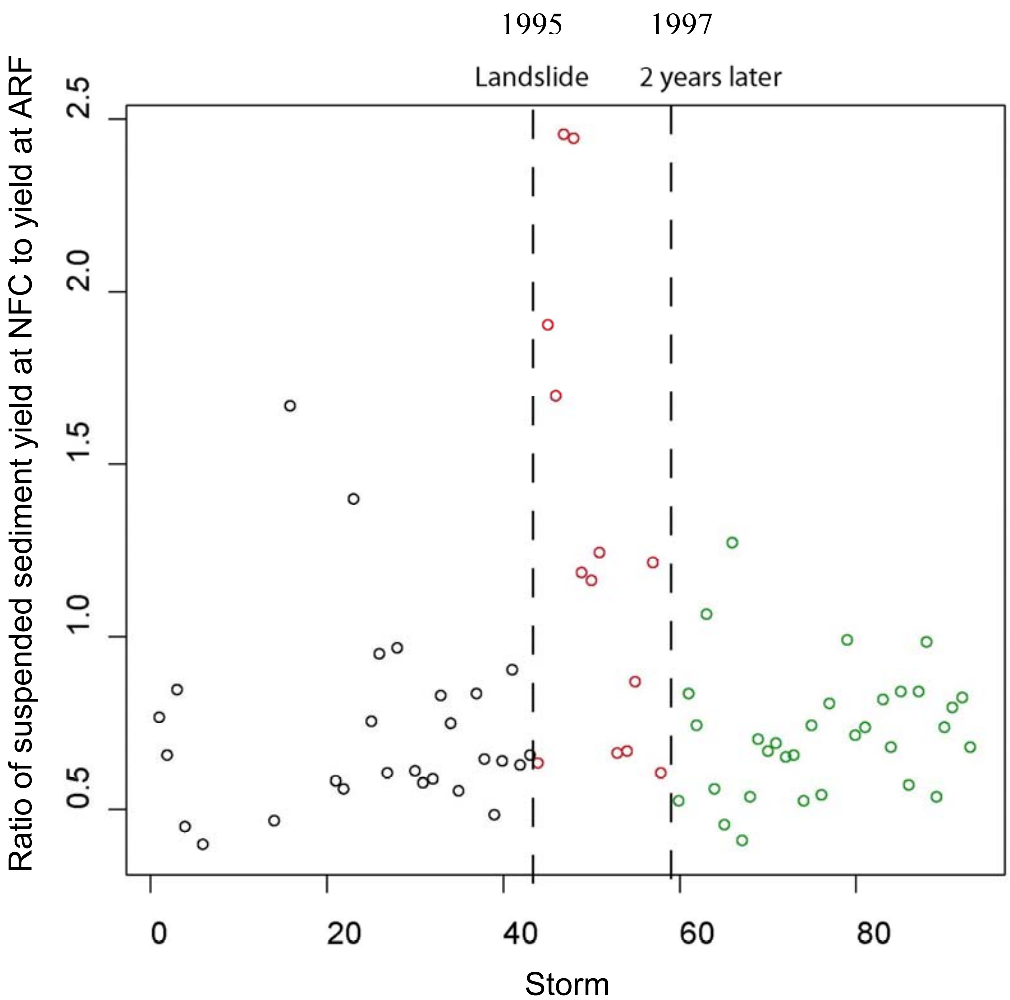

Figure 31. Ratio of storm sediment yields upstream (ARF) and downstream (NFC) of the confluence of the North Fork with the XYZ subwatershed (site of the large1995 slide). Storm number is based on the chronological order of storms gaged at Caspar Creek starting in the hydrologic year 1986. The sample includes all storms for which sediment was recorded successfully for both NFC and ARF (many of the early storms were not successfully measured at gage ARF and are not included in this set produced more

sediment than the channel had capacity to easily remove, may have partially blocked transport of upstream sediment.

Approach 5: Correlation of Gully Dimensions With Sediment Output

If sediment produced from gully banks can account for sediment output, (as outlined in approach 2), then one might expect some correlation between sediment output and the area of gully banks present. Two logical time periods for this analysis are determined by the periods of record available for the gages: from 2001 to 2003 in the South Fork tributaries and some of the North Fork tributaries, and from 1986-1995 in all North Fork tributaries. The period 1996-2000 is less fruitful for data analysis because only five stream gages (all on the North Fork) were operational. Comparison of gully measurements taken in summer 2001 with gage data from 1986 to 1995 on the North Fork depends on the assumption that the sizes of gullies did not change significantly between 1995 and 2001. This assumption seems reasonable given that the presence of large gullies in the control watersheds indicates that gullies are likely to have already been present for about a century before second-cycle logging.

Average depth and bank area per unit area were explored as two non-area-dependant variables that might correlate with unit-area suspended sediment yield. Average depth showed a slightly higher correlation with sediment output than bank area per unit area, but p values indicate that neither correlation is very strong, and neither is significant for both time periods (Figure 32, Table 7). Watershed area was also examined as a possible predictor of sediment per unit area (Figure 33), on the theory that larger

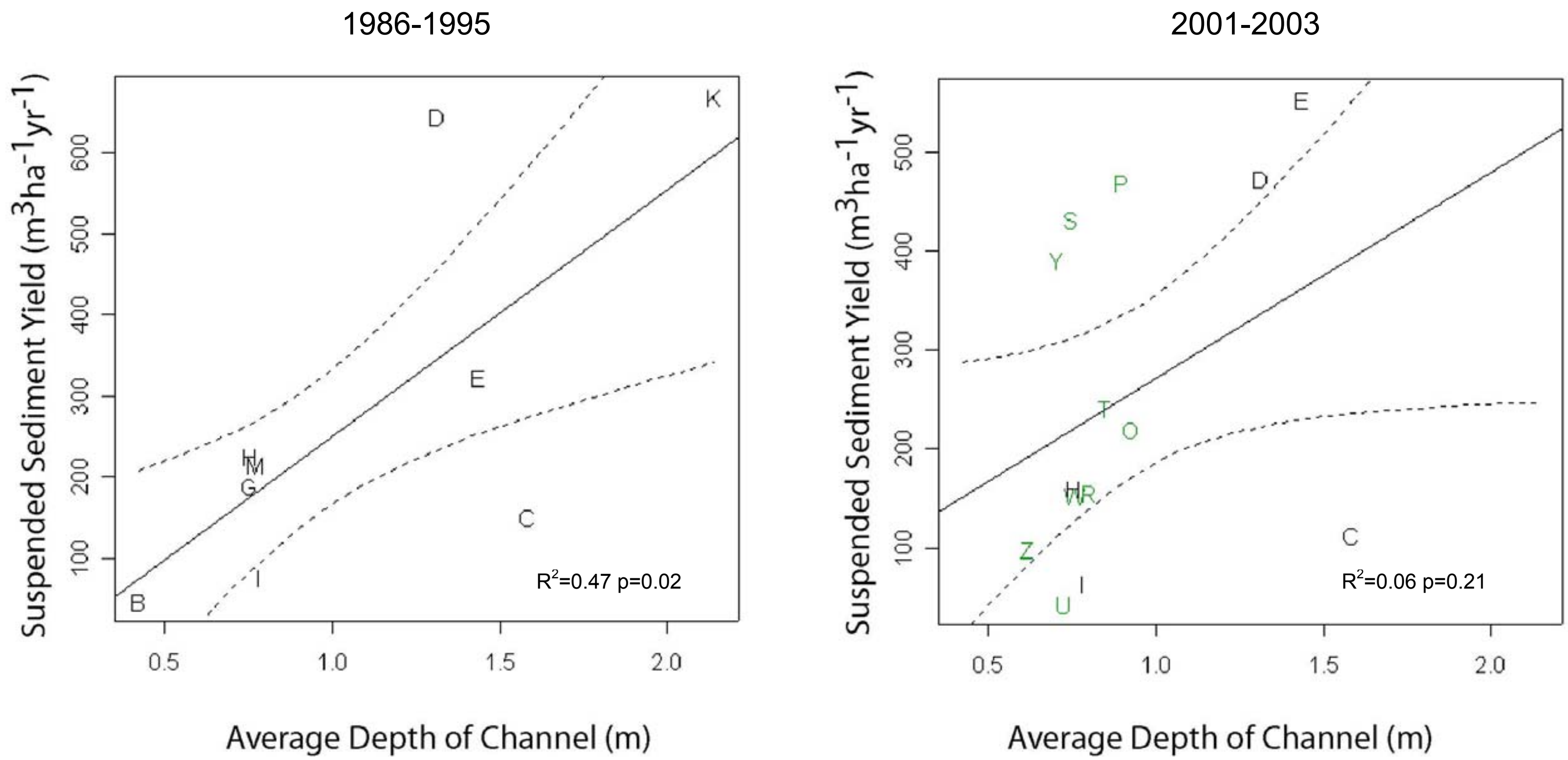

Figure 32. Comparison of average channel depth with sediment output.

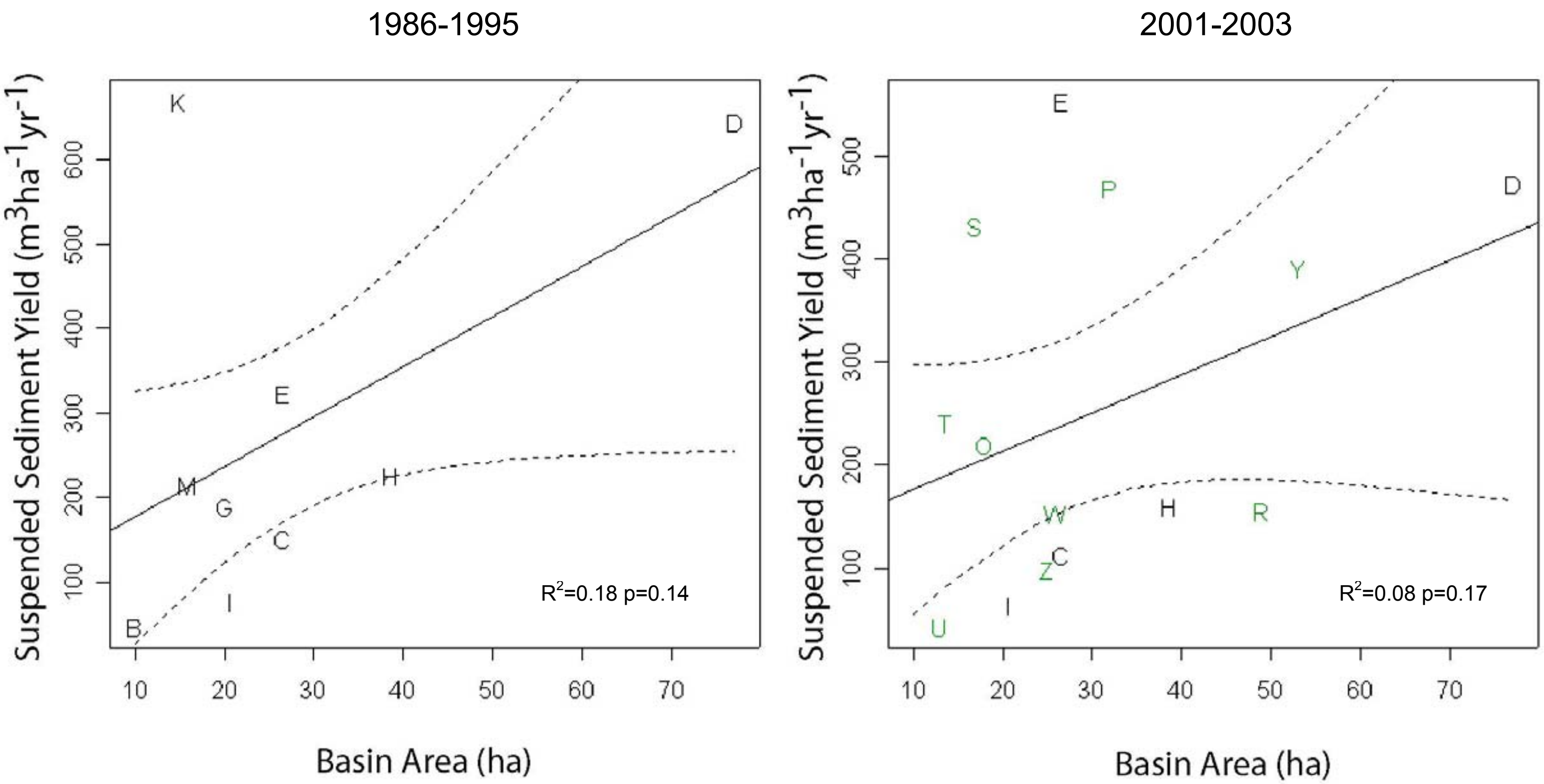

Figure 33. Comparison of basin area with suspended sediment yield.

watersheds might exceed a threshold for channel initiation over a larger portion of their watershed, but there was no statistically significant correlation (Table 7). As was the case with hillslope erosion measurements, simple parameters for eroded channel dimensions fail to predict sediment delivery.

A model based on multiple regression of area and average channel depth appeared promising for predicting suspended sediment output in the older data set, but failed to hold up in the newer data set. In a complex system such as Caspar Creek, inherent temporal and spatial variability in such factors such as sediment storage along the channel, bank erosion rates, subsurface erosion, headcut erosion, and non-channel sediment inputs are likely to introduce a level of complication beyond easy prediction based on one or two simple parameters.

Summary of Five Approaches to Assessing Importance of Gullies

In summary, four of the above approaches support the idea that gullies are important sediment contributors, while the results of the regression analysis are ambiguous. The importance of gullies as sediment producers is suggested by the increased output at gage DOL in the two years after second-growth logging in the upstream EAG watershed. Gullies also seem a likely cause of the increased sediment output at YOC relative to ZIE. Banks of these channels are extremely unstable and bank retreat could easily deliver sediment directly to channels in excess of what is observed at stream gages. The gullies are large enough that they would have had to produce sediment

Table 7. Summary of regressions of sediment per unit area as compared with bank area/area (with and without key depositional reaches as sediment filters), average channel depth, and basin area.

Period	Fork	Predictor	Depositional Reach Cutoff used?	Adjusted R^2	p
1985-1995	NFC	Bank Area/Area	No	0.16	0.15
2001-2003	Both	Bank Area/Area	No	-0.08	0.88
2001-2003	SFC	Bank Area/Area	Yes	0.13	0.18
1985-1995[1]	**NFC**	**Bank Area/Area**	**Yes**	**0.40**	**0.04**
2001-2003	Both	Bank Area/Area	Yes	0.003	0.32
1985-1995	**NFC**	**Average Depth**	**No**	**0.47**	**0.02**
2001-2003	Both	Average Depth	No	0.06	0.21
1985-1995	NFC	Area	N/A	0.18	0.14
2001-2003	Both	Area	N/A	0.08	0.17
1985-1995	NFC	Hillslope Erosion (Rice, 1996)	N/A	-0.02	0.39
1985-1995	**NFC**	**Multiple Regression: Average Depth and Area**	**N/A**	**0.62**	**0.02**
2001-2003	Both	Multiple Regression: Average Depth and Area	N/A	0.09	0.24

[1] Results significant at the 0.05 level are indicated in bold font.

in significant quantities relative to what is typically seen at gages just to achieve their size in the last 120 years. Hillslope sediment inputs, while considerable, fail to explain sediment output in channels except shortly after large events, suggesting that channel sediment sources might be important.

Overall, results of the first four approaches described above suggest that gullies are an important component to understanding the sediment budget. While the fifth approach, regression analysis based on simple gully geometry, did not demonstrate that gullying is the primary control on recent sediment production, results of several of the regressions are consistent with the hypothesis that gullying remains an important influence. It may be useful to develop an index of recent gully activity to use in such analyses instead of simple descriptions of gully geometry.

DISCUSSION

Gullies and Overall Sediment Production

The data presented allow calculation of an approximate sediment budget. In an earlier section, I estimated sediment displacement on hillslopes by large landslides alone to be 1300-1650 kg $ha^{-1}yr^{-1}$. Rice's data suggest an overall hillslope soil erosion rate of 7,150 kg $ha^{-1}yr^{-1}$ for North Fork tributaries (Rice 1996). It should be noted that Rice's figure includes watersheds that were logged during the course of his study and exhibit much higher rates of hillslope erosion than observed in controls, so this value is unlikely to represent a long-term rate. Both of these figures are far higher than the 435– 990 kg $ha^{-1}yr^{-1}$ estimated for bank erosion by assuming that banks recede between 1 and 1.8 cm per year, average active bank density throughout the study area is 36.8 m^2ha^{-1}, and bulk density is 1185-1500 kg m^{-3}. Both hillslope and channel sediment production estimates far exceed the mean observed suspended sediment yields at stream gages of 255 kg $ha^{-1}yr^{-1}$ from 2001 through 2003 and 280 kg $ha^{-1}yr^{-1}$ from 1986-1995 (Figure 34).

The sediment budget is likely to fluctuate on a year-to-year and storm-to-storm basis, as well as between subwatersheds. Though the lines of evidence developed in the previous section suggest that sediment eroded from gullies is an important component of the sediment exported from tributary watersheds, erosion processes on hillslopes apparently displace more sediment than the channels do. However, hillslope sources are much less efficient than channel sources in delivering this sediment.

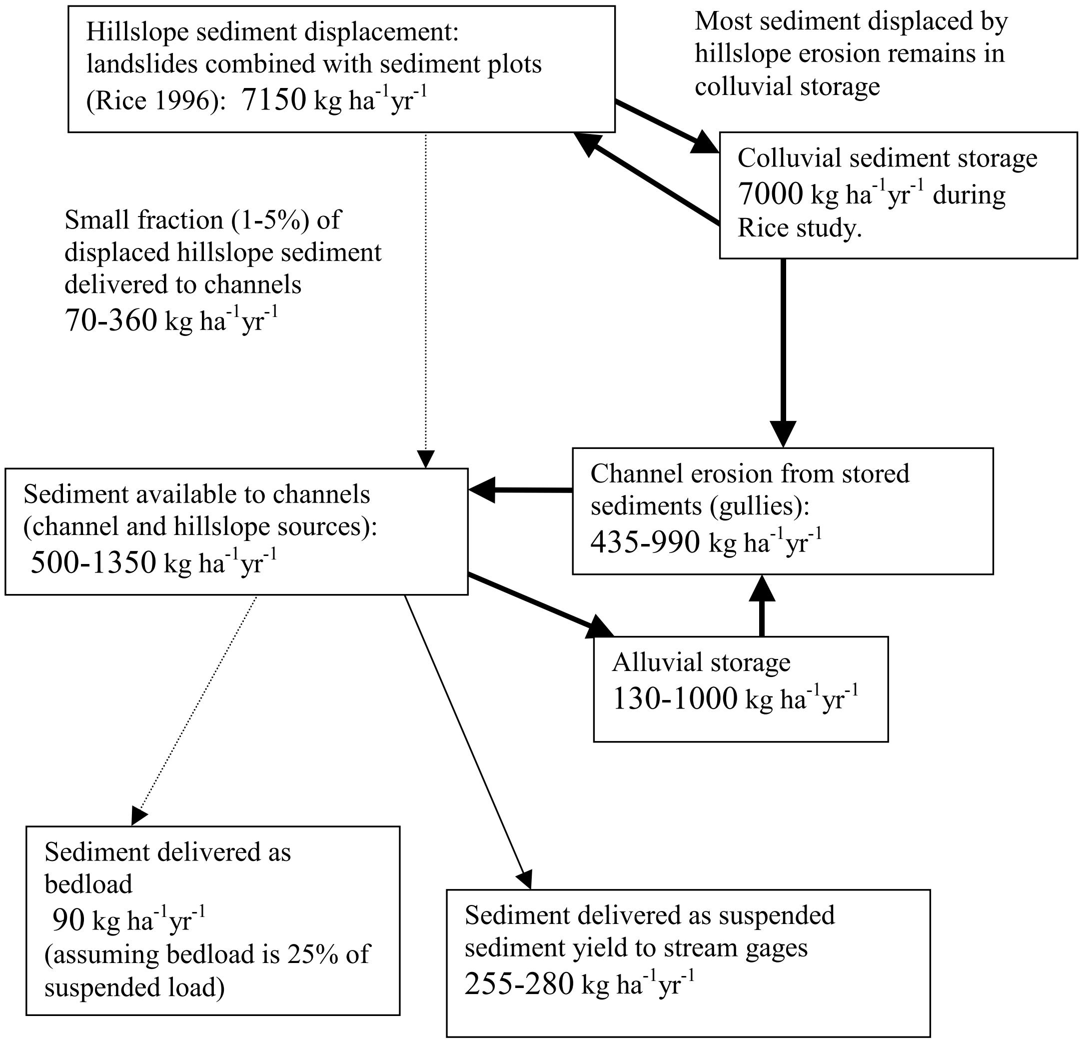

Figure 34: Estimated sediment budget over the decadal scale. Indicated rates are based on gully observations from this paper and from hillslope observations by Rice (1996). Error on these numbers should be considered large.

Though hillslope sediment production is estimated to exceed channel sediment production, it correlates so poorly with, and is so far in excess of, sediment output that we can conclude that most hillslope sediment that is displaced is not transported quickly out of the watershed. A high proportion of the displaced sediment must therefore contribute to colluvial sediment storage between production on the hillslope and channel delivery, implying that lower hillslopes and valley floors are sites of accumulating sediment.

In theory, this recently stored sediment could provide most of the sediment eroded by the gullies, but this does not appear to be the case for a substantial portion of sediment mined by the gullies. The gullies undercut old-growth stumps in many places, and they cut into many deposits old enough to contain well-developed gleyed clays, which can take millennia to form (Rose and others 1988). Gullies are mining sediment much older than the excess sediment produced by recent hillslope processes.

The sediment budget estimated for the area thus appears paradoxical when considered in context of the channel conditions: it calls for net colluvial and alluvial storage of sediment over the short-term, while the channels are obviously incising dramatically. The apparent paradox can be resolved if one accepts that over the short-term (decadal scale) the processes of erosion and deposition are not at equilibrium, that both colluvial and alluvial sediment are being stored outside of the incising channels, and that these channels are incising largely into older sediments. This may be analogous to observations of long residence time at Coon Creek (Trimble 1983), even though Caspar Creek is a much smaller and steeper watershed than Coon Creek.

Inferred History and Evolution of Caspar Creek Gullies

Overview

The sediment budget suggests a decadal-scale tendency towards storage of recently eroded hillslope sediment even while incision occurs simultaneously in channels. This situation suggests a lack of equilibrium over the decadal scale, and is a likely outcome if both gullies and elevated hillslope sediment output are consequences of disturbances that have occurred in the watershed since 1860.

Vegetation clues suggest that the gullies postdate and are a likely consequence of initial entry logging. Second-growth logging appears to affect gully growth as well, as illustrated by the sediment apparently produced from gullies in response to a period of increased stream flow in tributary DOL. However the precise nature of the effect of second-growth logging is harder to decipher because gullies were well developed prior to second-growth logging. The process of recovery from gullying is complex, and the incision cycle appears to be ongoing; multiple active headcuts are present even in control watersheds that were only logged once, 120 years ago.

Gully Erosion After Initial Entry Logging

The vegetation clues cited earlier suggest that gully erosion was dramatic following the initial logging entry. The early logging, yarding, and burning would have had several influences on channel growth. Runoff would have increased with the loss of canopy, loss of duff through burning, and compaction caused by logging operations. Removal of woody debris both for salvage and to ease yarding along valley axes would have removed resistant buffers to gully propagation. The process of transporting logs down to locations along the mainstem would have greatly disturbed compacted soil. All these conditions would have favored gully growth. Gully erosion would have been one component contributing to the aggradation observed downstream at the mouth of Caspar Creek. Once gullies formed, they continued to be sensitive to high storm flows even after trees started to grow back. Gullies, including fresh gullies, are surprisingly widespread in control tributaries MUN, HEN, and IVE, suggesting that a complex response from the initial gullying episode is still playing out.

Gully Erosion After Later Cycles of Logging

Further gullying clearly resulted from the second-entry logging on the South Fork, as incised road fill from this time period suggests. However, many of these gullies appear to be exploiting prior channel incisions. The longest continuous gullies are found in the North Fork (DOL and KJE), suggesting that pre-existing gullies were filled-in in many places during the second episode of South Fork logging.

Gullying may also have initiated as a result of second-cycle logging on the North Fork, but gullies in the clearcut areas were not completely mapped due to the difficulty of moving in slash and seeing channels. Gage evidence (specifically in DOL, where all logging was upstream of the area in which the increase in sediment originated) suggests that existing gullies downstream of clearcuts were stimulated to grow more quickly and produce more sediment. This is similar to the observation by Heede (1985) of increased channel erosion in buffered channels downstream of a logged watershed in Arizona.

Multiple Headcuts

The presence of multiple headcuts in all Caspar Creek tributaries, both upstream and downstream of bedrock controls, indicates that incision is occurring independently at many places in each subwatershed rather than being generated by a single headcut migrating from a base position all the way up each tributary. The existence of multiple headcuts in tributaries upstream of the splash dam shows that splash damming on the mainstem channel could not have been the trigger for the majority of the gullies. Even the large gully at the base of tributary KJE is upstream of the base-level control exerted by the remainder of the splash dam deposits downstream.

However, there are places where it is reasonable to assume that particular headcuts may have migrated considerable distances upstream. Headcuts can maintain their definition, shape, and size as they migrate. For example, the headcut YOC 20 (Figure 24) still maintains a vertical face after undercutting the roots and migrating 3 meters upstream.

Channels are often incised for some distance downstream of headcuts, and often other headcuts are present within the incised reaches. These nested headcuts often cut into an underlying substrate of ancient alluvium, colluvium, or saprolite that is deeper than recent alluvial deposits, causing an incision that is deeper than the original gully, rather than simply gullying through material deposited from the upstream headcut. This situation is very different from that described by Schumm (1973), where gullies form on steepening alluvial fans deposited from upstream gullies.

Two scenarios might explain the presence of nested headcuts. In the first case, a downstream headcut could simply migrate upstream into a gully created by the earlier migration of the upper headcut. In the second scenario, small obstructions, formed by infalling woody debris, might initiate plunge-pool erosion on the floor of a gullied channel, causing a headcut to grow and eventually migrate. Either scenario could lead to gullies that cut deeper than the sediment that had accumulated on the floor of the upstream gully, leading to a compound gully that deepens in places downstream of the upper headcut.

The presence of multiple headcuts is not necessarily a predictor of high sediment output in Caspar Creek watersheds. Some watersheds, such as UQL, have a high headcut density but relatively low suspended sediment output. Sediment output is much higher in the downstream reach of DOL, even though headcut density is lower (Tables 2 and 3). In contrast to the closely spaced UQL headcuts that delineate the upstream end of multiple short incised reaches, the more sparsely placed DOL headcuts delineate the upstream ends of long reaches of entrenched channel.

The existence of multiple independent locations of incision within all subwatersheds of Caspar Creek is important because it implies that incision initiated in response to a change in inputs and conditions throughout the watershed, rather than being caused by upstream propagation of a disturbance. This conclusion is consistent with the hypothesis that gully growth was triggered by increases in runoff in combination with widespread channel and valley-axis disturbance during initial logging.

Gully Evolution

Gullies are both a response to a disturbance and a disturbance themselves to the channel network. Even after conditions that caused gully initiation have subsided, gullies can continue to grow if adequate channel flow allows for removal of sediment generated from headcut and bank retreat.

With channels still very gullied, recovery from the initial logging will probably take hundreds of years. Although data presented by Lewis (2004) suggests that tributary sediment loads from second-cycle logging had recovered by about 2000 to levels characteristic of the tributaries before second-cycle logging, the overall recovery process for gullies is probably much more gradual. It is unclear how second-growth logging affected the long-term evolution of these gullies.

Long-term recovery may be gradually occurring in some gullies showing relatively low activity levels. These gullies appear dormant with diffusing banks and accumulations of duff in the channel, but this could easily be reversed by a period of heavy precipitation or otherwise increased flows from upslope. Because the focus of this study was on other aspects of gullying, the study generated little quantitative data on these apparently dormant gullies, beyond the observation that they exist. The mapped, active gullies appear quite capable of continuing to grow.

Caspar Creek currently includes examples of channels of all six states mentioned by Simon and Hupp (1986). Channels which have reached a state of quasi-equilibrium upstream of headcuts could be considered in stage 1 (premodified); stage 2 (constructed channels) could include sections where roads and skid-trails interact with the channel;

stage 3 (degradation prior to widening) would include gully sections with rapidly migrating headcuts; stage 4 (degradation and widening) occurs where flows undercut vertical banks; and stage 5 (aggradation and widening) occurs as banks widen to the point where the channel is no longer able to interact with them. Stage 6 reaches (quasi-equilibrium channels that are neither aggrading nor incising) might include the large old gullies with revegetated walls, though these often become the sites of stage 2 through stage 5 gullies growing up their axes.

CONCLUSIONS

Gullies are widespread at Caspar Creek. Gullies and headcuts are found in all first- and second-order tributaries, and most of the length of each tributary channel is incised. Channels are still recovering from events that occurred over 100 years ago, but they are also sensitive to further disturbance. The gully pattern is quite complex, with multiple headcuts excavating gullies in stages.

Once formed, gully headcuts and walls can be stimulated to fail and produce sediment by increases in stream flow. Resistant elements appear to be important buffers to headcut migration. Headcut migration can be of different modes: gradual (0-15 cm yr^{-1}) or dramatic (exceeding 1 m yr^{-1}). Estimates from two sets of observations--a larger population of headcuts observed for dramatic change and a smaller population of headcuts surveyed for more subtle change--result in a rough average headcut erosion rate of 6 cm yr^{-1}. Measured retreat rates are strongly bimodal: gradual retreat occurred on about half of the headcuts in a given year, while dramatic retreat occurred on 0-6% of the headcuts.

Observations also suggest that the portion of the headcut that retreats is often narrower than the width of the channel immediately downstream of the headcut (Figure 23), indicating the relatively importance of gully-bank erosion. Bank retreat is estimated to be in the range of 1-2 cm yr^{-1} in active gullies, which would produce abundant sediment relative to the sediment yields observed at gaging stations.

Evidence that gullies are important can be summarized in four statements: 1) gully erosion is a logical cause of increased sediment production noted at the downstream end of two sets of nested stream gages, DOL-EAG on the North Fork and YOC-ZIE on the South Fork; 2) measured rates of bank and headcut retreat that deliver sediment to the channel network would easily produce an amount of sediment that exceeds sediment delivered to stream gages; 3) estimates of the long-term average rate of gully sediment production based on gully volume and age suggest that gullies must have contributed considerable sediment over the past 120 years; 4) data on hillslope sediment production indicate that the distribution of measured non-gully sediment sources does not appear to explain why a tributary channel would characteristically produce more or less sediment then another channel. Examination of a fifth line of evidence provides ambiguous results: some correlation exists between gully dimensions and annual sediment production during some time periods but not others; results appear to be influenced by other sediment producing events and by conditions in the specific tributaries analyzed.

Routing of sediment from the watershed is complex. It is likely that gullies play an important role in excavating stored sediment. Despite this role, the incising channels have not yet reached most of the stored sediment in the watershed. Landslides can generate large amounts of sediment, but much of this sediment appears to remain in colluvial storage for a long time, as estimates of hillslope sediment production are poor predictors of sediment output. The tributary watersheds are capable of storing sediment for thousands of years, as evidenced by gleyed clays and undercut old-growth stumps on formerly stable deposits. Sediment displaced on hillslopes in significant erosional events should not be assumed to be leaving the watershed in the same event.

Recovery of gullies appears to still be at a relatively early stage. Signs of recovery include gullies that have filled with duff and vegetation (unmapped), and gully walls that have started to recede, allowing flow to spread out and lose power. The mapped gullies still have active headcuts and appear capable of continuing to grow both upstream through headcut retreat and laterally through bank erosion. It is unclear how the recent pulses of sediment from second-entry logging in both the North and South Forks will affect gully recovery in the long run. The gullies provide a mechanism by which flow pulses can lead to dramatic downstream sediment delivery, even if hillslope sediment sources are buffered from channels. The complex response in the channels includes some reaches which are actively gullying downstream of reaches which have previously been gullied but are now stabilized. The gullies will likely continue to produce noticeable sediment for years.

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