SEDIMENT BUDGET STRATEGY FOR JACOBY CREEK WATERSHED, HUMBOLDT COUNTY, CALIFORNIA

A report to Redwood Community Action Agency

by

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INTRODUCTION

This report describes a strategy for developing a sediment budget for the Jacoby Creek watershed in Humboldt County, California. Key tasks for this strategy were:

- Estimate sediment yield from the Jacoby Creek watershed,
- Compile a list of and summarize existing information that could contribute to a sediment budget, and
- Identify key information gaps and recommend additional, cost-efficient studies to fill those gaps.

A wealth of information exists that describes the Jacoby Creek watershed, most likely due to its relatively small and therefore 'manageable' size, its close proximity to Arcata and researchers from Humboldt State University and the USFS Redwood Sciences Laboratory (RSL), the purchase of land and conservation easements by the City of Arcata and the Jacoby Creek Land Trust, and by watershed residents that take an active interest in the health of the watershed. In 1999, an HSU class taught by Dr. Y. Everett compiled an extensive bibliography for Jacoby Creek (Everett, 1999) that described the considerable body of written knowledge of Jacoby Creek. Frakes (1989) performed an interdisciplinary examination of two water quality issues in Jacoby Creek: bacterial contamination from septic systems and sedimentation of the creek impacting salmonid habitat. Murray and Wunner (1980 and 1988) compiled much descriptive information on Jacoby Creek. Collectively, these documents show that there is already much known about Jacoby Creek and attest to the high level of interest in the well-being of this small watershed.

Jacoby Creek drains about 19 square miles of land, with most of this (about 80%) consisting of timbered hillslopes and the rest of low gradient pasture, wetlands, and residential lands located on floodplains and terraces bounding the creek. The creek flows into Arcata Bay just south of Arcata, California. Although the creek has no tide gates at the downstream end where it meets Arcata Bay, much of the channel flowing through the bottomlands is lined with earthen levees that restrict flooding to the bankfull channel width. Levees are discontinuous in several locations, having been breached by bank erosion and by local residents.
Unlike other Humboldt Bay tributaries, Jacoby Creek has a relatively steep gradient virtually all the way to Arcata Bay, as evidenced by coarse bed material on the channel bed just a few hundred yards upstream of Highway 101 (Fig. 1). While tide-induced backwater influences flooding during stormflows for a substantial distance upstream of Arcata Bay, salt water appears to only extend a relatively short distance upstream from the bay as evidenced by a lack of characteristic intertidal plant species beyond a few hundred feet upstream of Highway 101 (personal observations, 2003).

Sediment Budget Description

According to Reid and Dunne (1996):

> *"A sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin."*

Reid and Dunne (1996) describe many of the challenges of sediment budgeting and offer numerous methods for estimating various components. A sediment budget can be described by the equation below:

$$\mathbf{I + \Delta S = O}$$

where 'I' represents inputs of sediment to the channel system (erosion and sediment delivery), 'ΔS' represents changes in sediment storage within the channel system, and 'O' represents output of sediment

from the watershed. Typically, one or two of the variables are known with more accuracy than the other(s). When estimates for each variable are derived, an attempt is made to balance the equation with the greatest skepticism placed on the least accurate term in the balancing process.

In its simplest form, a sediment budget attempts to balance basin sediment yield (the volume or mass of sediment passing a given point within the watershed, often chosen as the basin outlet) against erosion and sediment storage within the watershed over some time period of interest. Depending on the intended uses for the sediment budget, more complex forms might target specific issues, such as determining the relative or absolute contributions to the budget from natural versus human-caused erosion sources, or the contributions from contemporary versus 'legacy' land uses, or the contributions from various erosion processes (e.g., surface erosion, landslides, channel erosion). These are the most common issues addressed in sediment budget studies, and the usefulness of such studies in basin land use planning, adaptive management, and watershed restoration is well-recognized. It is vital to develop clear goals and objectives for the sediment budget prior to its commencement to ensure that the data gathered and the form of the analysis are appropriate for the intended uses.

The most accurate sediment budgets consist of a detailed accounting of erosion, sediment storage, and sediment yield based on spatially- and temporally-dense field measurements. However, such studies are only possible with a great commitment of time and money, as in experimental watershed research projects (e.g., Caspar Creek in the Jackson State Forest, Mendocino County). On the other end of the scale, more expeditious methods can also provide information quite useful for watershed assessment and planning (see Reid and Dunne, 1996). Of practical necessity, a sediment budget for Jacoby Creek will follow the latter approach, as dictated by the availability of existing information and funds for filling data gaps and will require estimates, rather than measurements, of the rate of erosion and sediment delivery from most sources. Estimates will likely be best derived from detailed studies done elsewhere in climatologically and geologically similar areas, however, some ground-truthing and adjustments will be required for reliably applying data to Jacoby Creek from another area.

Erosion and Sedimentation Processes

Erosion is the physical displacement of soil, regolith, underlying bedrock, colluvium (sediment stored on the hillslope), or alluvium (channel and floodplain deposits) from one location to another. The primary erosion processes of interest on the northcoast are:

> ***Surface erosion***: rainsplash and sheetwash on bare soils, rill and gully erosion;
> ***Fluvial erosion***: channel erosion, including bed and bank scour;
> ***Mass Movements***: slumps, earthflows, debris slides and torrents, and soil creep.

Not all eroded material immediately enters the stream system when displaced from its original location: some may remain stored on hillslopes for time periods of varying length, from days to decades or longer. Typically, we are most concerned when erosion processes deliver sediment to a channel ('sediment delivery', or input in the sediment budget equation) due to potential impacts to aquatic habitat and channel physical conditions . Once delivered, it may be transported out of the watershed (output), or come to rest in discrete compartments, such as upstream of log jams, or it may be deposited over long lengths of channel, causing extensive 'aggradation'(increased storage).

In the case of fine sediment, some may be deposited on floodplains adjacent to the channel, becoming 'inactive' (effectively removed from the active sediment transport regime) for long periods. Collectively, these terms represent forms of 'sedimentation'. Over the near term, sediment delivered during large, infrequent events may be deposited and stored in all of these forms, with some proportion also transported out of the watershed. Previously deposited sediment within the active channel system may also be re-mobilized and move downstream during storms, possibly out of the watershed.

Over the longer term, most sediment delivered to the channel will eventually leave the watershed. However, as described above, hillslope and channel storage processes may cause an imbalance between erosion and sediment yield over the time period of interest. This imbalance is represented by the 'storage' term of the sediment budget equation.

Geology and Geomorphology

Geologic conditions in Jacoby Creek are also fairly well-known. Several mapping projects have been undertaken, primarily by researchers with Humboldt State University. Lehre and Carver (1985) describe the geology of Jacoby Creek as follows:

> '*The upper slopes of Fickle Hill consist largely of Franciscan melange and greywacke which have been thrust southward over Pleistocene shallow marine and continental sediments of the Falor Fm (Carver and others, 1982; Carver and Stephens, 1983; Carver, this volume). Falor sediments form much of the lower slopes of Fickle Hill. A small, nearly-horizontal patch of Falor sands lies in depositional contact with Franciscan melange on the crest of Fickle Hill (fig. 2 and Carver, this volume). Kneeland Ridge consists chiefly of Franciscan rocks with a thin veneer of northeast-dipping Falor Fm – again in depositional contact with the Franciscan – present locally near the creek*'.

The Jacoby Creek Land Trust (JCLT) produced an initial assessment of watershed conditions that included maps showing slope classes and geomorphic features related to landsliding (JCLT, 1997). They, as well as the City of Arcata Environmental Services Department, also maintain GIS data and products that would be useful for constructing a sediment budget.

Alpert and Durgin (1985) investigated slope stability and prepared maps for a 560 acre parcel adjacent to Jacoby Creek , part of the City of Arcata's Community Forest. Their work was directed at identifying slope stability hazards to be incorporated into the City's forest management practices. The area is underlain by predominantly by Franciscan melange and coherent sandstone overlain by scattered remnants of Falor Formation marine sediments and alluvium. They found that debris slides dominated mass movements in the sandstone units while earthflows were dominant in the melange units and recommended practices appropriate to the various geologic and geomorphic areas within the forest.

Additional information on the geology and geomorpholgy of the Jacoby Creek watershed can be found in a variety of sources, including maps produced by several agencies, a doctoral dissertation by Tuttle (1985), several master's theses done by HSU students, and technical articles published in a variety of forums (journals, conference proceedings, etc.). These are listed in the bibliography at the end of this report.

A watershed analysis was done in 1996 by forestry students at HSU (Conroy and others, 1996). For this analysis, they compiled geologic mapping of Kilbourne (1985) into a GIS database and calculated the areas of the geologic formation reproduced in Table 1, below.

Table 1. Areas of geologic formation in Jacoby Creek (from Conroy and others, 1996; based on mapping in Kilbourne, 1985). (Note: this does not include the entire watershed, estimated at about 12,160 acres).

Geologic Formation	Area (acres)	% of Watershed Area
Franciscan Melange	5053	47
Broken Franciscan	2320	21
Hookton	1364	13
Quaternary Alluvium	2110	19
Total	**10,847**	**100**

Slope steepness exerts a major influence on erosion processes and susceptibility of hillslopes to instability following disturbance. The Jacoby Creek Land Trust, along with the City of Arcata, developed a slope class map based on a digital elevation model (DEM) of Jacoby Creek that also included the adjacent Washington Gulch and Rock Gulch watersheds. Slope classes are color coded, providing a powerful visual tool for identifying areas of generally steeper slopes. The slope class data were also summarized, as shown in Table 2.

Table 2. Slope classes from data compiled by the Jacoby Creek Land Trust and the City of Arcata (Note: these data include Jacoby Creek, Washington Gulch, and Rocky Gulch).

Slope Class	Area (acres)	% of Watershed Area
0-20%	4,762	37
20-35%	4,585	35
35-50%	2,247	17
50-65%	883	7
>65%	541	4
Total	**13,018**	**100**

Land Use

Hillslopes within Jacoby Creek are dominated by forest cover of varying ages, although a some grassland areas are also located on slopes near the ridge tops that are used for grazing and private residences. Timber harvest is the most spatially-extensive land use within the watershed. Residential development is primarily concentrated in the valley bottom and along Fickle Hill Road in the northeastern headwaters. In addition to natural sources of sediment delivery, these disturbances have the potential to accelerate erosion and sediment delivery, particularly where located on steeper hillslopes.

Table 3 shows broad land use categories in Jacoby Creek as of 1995 (note that land transfers since 1995 may have changed these values). Together, several large timber companies own and most of the forestlands in Jacoby Creek and actively manage their lands for timber production. The City of Arcata owns several large forested parcels and manages for sustained, low impact timber production and recreation. The Jacoby Creek Land Trust, a non-profit group, owns several parcels of bottomland with management goals of open space preservation and restoration. The remaining lands in Jacoby Creek consist of medium to small ranches in the bottomlands and private residences (some in subdivisions) distributed among bottomlands, hillslope areas adjacent to the valley bottom, and homes distributed on hillslopes along the main channel upstream of the valley head and along Fickle Hill Road.

Table 3. Distribution of land use categories in Jacoby Creek (adapted from Conroy and others, 1995; original source: Humboldt County Tax Assessor).

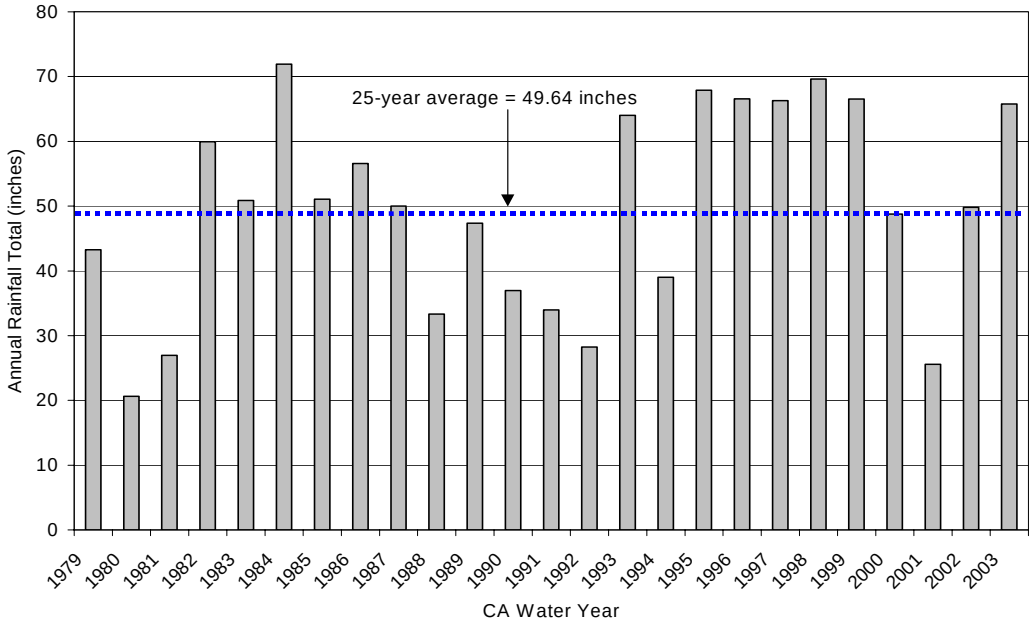
Land Use Category	**Acres**	**% of Watershed Area**
Timberland	7289	67
Residential	2805	26
Agriculture	753	7
Total	**10,847**	**100**

Land use is well documented in coastal northern California and elsewhere as a potentially large contributor to elevated erosion and sediment yield. Residential developments can contribute to surface erosion primarily during construction if vegetation clearing and earthmoving occur. Access roads to residential developments can also pose risks of surface erosion of the road surface, cutslopes and fillslopes as well as landsliding and gullying. Timber harvesting and associated road construction and use also play a large role in elevated erosion and sediment yield, both due to delayed effects of older practices (termed 'legacy' erosion) and current practices.

Rainfall

Erosion and sedimentation are event-driven, with most occurring for relatively brief periods of intense rainfall and high streamflow. Erosion and sediment delivery to streams and sediment transport in streams can vary greatly from storm to storm and year to year. Rainfall can be useful as a rough index of erosion and sedimentation activity. Although no long-term recording rain gage exists in the basin, average annual rainfall is estimated to be about 50 inches from an isohyetal map (Miller and others, 1973). This agrees well with the average of two recording rain gages that are near the upper and lower extremities of Jacoby Creek: 62.62 inches per year at Kneeland (headwaters) and 38.51 inches per year in the City of Eureka (near the basin outflow) (from "California Rainfall Summary 1849-1980", California Dept. of Water Resources, 1982). In addition, a storage rain gage has been maintained in the Jacoby Canyon area (near the mid-basin point) by a Jacoby Creek resident since 1979 (R. Lewis, pers. comm.). That rain gage was read nearly daily for the 25-year period, and the average annual rainfall (49.64 inches, see Fig. 1) is in close agreement with the average of the other two gages.

Figure 1. Annual Rainfall (July-June) for Jacoby Creek Canyon, 1979-2003 (from R. Lewis)



Hydrology

Lehre and Carver (1985) estimated mean annual discharge for the upper third of the watershed (at the former USGS stream gage No. 11-4800, 6.07 sq. mi.) to be 15.1 cubic feet per second (cfs), and for the lower main channel at the Brookwood Bridge (12.3 sq. mi.) to be about 30 cfs. Of primary interest for sediment budget studies are peak flows produced by short duration, intense rain storms. Figure 2 shows flood frequency curves developed for the upper watershed by Dr. Andre Lehre of Humboldt State University using annual maximum peak discharges measured by the USGS while they ran the gage (1955-1974). As indicated, a 10-year recurrence interval flood is estimated to be about 1600 cfs by the log-Pearson distribution (preferred), a 50-year about 2500 cfs, and a 100-year flood about 3000 cfs. Flood discharges for points lower in the watershed can be roughly approximated by increasing these values proportional to drainage area between the gage location and the point of interest.

The former USGS gaging station, abandoned by the USGS in 1974, was re-occupied by the USFS, Redwood Sciences Laboratory in November, 2000, and continues today. In addition to stream stage (water level, from which discharge can be estimated), the present station also records turbidity and has automated water sampling for suspended sediment concentration (SSC). Together, the recorded data and SSC allow relatively accurate estimation of suspended sediment yield for the upper watershed.

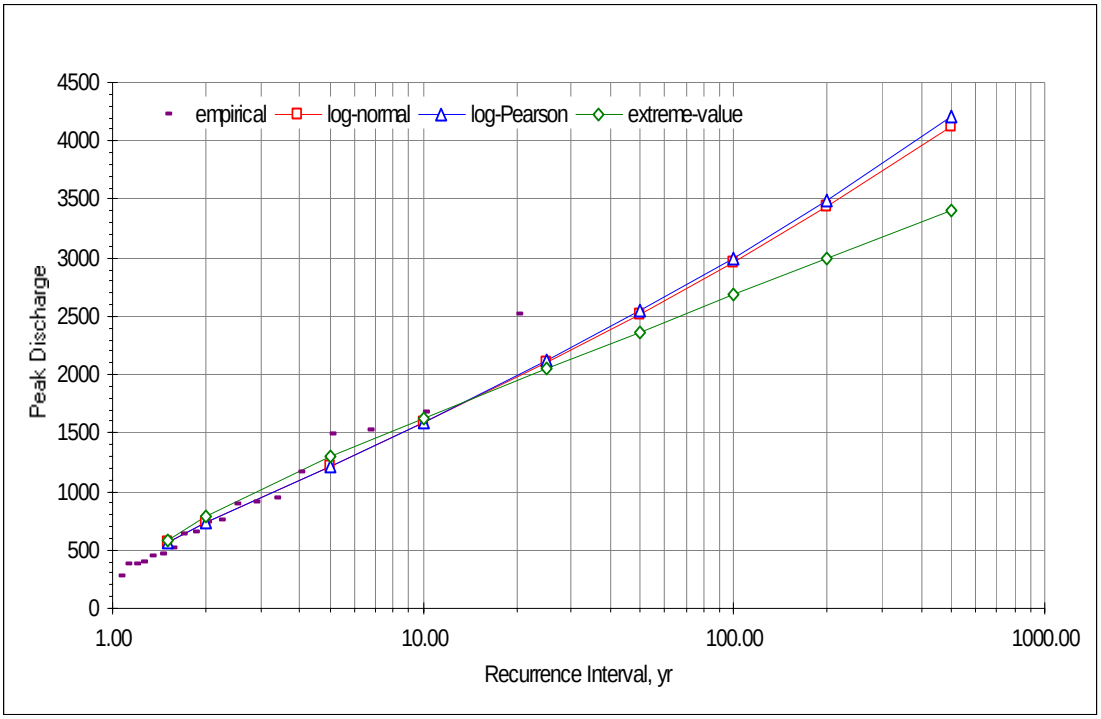


Figure 2. Flood frequency curves for Upper Jacoby Creek at former USGS stream gaging station No. 11-4800 (Drainage area = 6.07 sq. mi.). Measured floods (empirical data) are shown along with estimates for three types of distributions, with log-Pearson most commonly used (adapted from unpublished data by A. Lehre, Humboldt State University).

Beginning in December, 2002, I installed a recording gaging station at a location in the lower watershed (near the South Quarry Road bridge, drainage area = 11 sq. mi.). This station also recorded stage and turbidity and included manual water sampling. In December, 2003, the station was moved downstream to the Brookwood Bridge (drainage area = 12.3 sq. mi.), and will continue to be operated indefinitely. The

newer site at Brookwood is at the same location where hydrological monitoring was conducted by the USFS Redwood Sciences Laboratory (RSL) from 1979-1986. During this earlier period, sampling for both SSC and bedload transport took place, along with a host of other data collection (e.g., stream cross sections, longitudinal profile, bed material particle size analysis, etc.).

In addition, a non-profit group (Salmon Forever) has conducted storm sampling for SSC and stage or discharge for the past several years at several locations and streamflow has been recorded on Morrison Gulch (drainage area = 1.0 sq. mi.) for the past two years by researchers with Humboldt State University's Engineering Department (Dr. Margaret Lang, pers. comm., December, 2003). Most recently, additional stormflow sampling for turbidity began this winter on tributaries and main channel locations between the recording stations on Upper and Lower Jacoby Creek for a senior thesis project (N. Murano, Humboldt State University) with the objective of determining major locations of suspended sediment inputs between the two gages.

Table 4 lists all known hydrologic monitoring previously or presently conducted in Jacoby Creek. As indicated, there exists a fair amount of information on stream discharge, turbidity and SSC for Jacoby Creek that will be valuable for constructing a sediment budget, leaving the other components (sediment delivery and storage) to be measured or estimated. Of greatest utility will be data from the two recording stations (Upper and Lower Jacoby Creeks), as continuous data sets will allow relatively accurate estimates of sediment yield to be developed.

Table 4. Hydrologic monitoring sites and data for all known locations in the Jacoby Creek watershed.

Location	Drainage Area (mi^2)	Data Collected[1]	Period of Record	Operator[1]
Main Stem Sites				
Upper Jacoby Creek	6.1	CS, Q	1955-74	USGS
Upper Jacoby Creek	6.1	MS, Q, SSC	1971	N.H. Pillsbury
Upper Jacoby Creek	6.1	CS, Q, CNTU, SSC	2000-present	RSL
South Quarry Road	11.0	MS, MNTU	2001-present	SF
South Quarry Road	11.0	ES, Q, ENTU, SSC	2002-2003	RK
Brookwood Bridge	12.3	MS, Q, SSC	1978-1984	RSL
Brookwood Bridge	12.3	MS, Q, MNTU, SSC	2001-present	SF
Brookwood Bridge	12.3	ES, Q, ENTU, SSC	2003-present	RK
Old Arcata Road	15.0	MS, MNTU, FV	2001-present	SF
US Highway 101	16.6	Q, SSC	1971	N.H. Pillsbury
Tributary Sites				
Morrison Gulch	1.0	Q, SSC	1971	N.H. Pillsbury
Morrison Gulch	1.0	ES, Q	2002-present	HSUE
Morrison Gulch	1.0	MS, MNTU, SSC	2001-present	SF, NM
Steep Cr (MM 1.65)	unknown	MS, MNTU	2001-present	SF
Mile Marker 1.20	unknown	MS, MNTU	2001-present	SF, NM
Snag Creek	unknown	MS, MNTU	2001-present	SF
Eric Creek	unknown	MS, MNTU	2001-present	SF, NM
Rebel Creek 1	unknown	MS, MNTU	2001-present	SF, NM
Rebel Creek 2	unknown	MS, MNTU	2001-present	SF
Last Fork 1	1.03	Q, SSC	1971	N.H. Pillsbury
Last Fork 2	0.78	Q, SSC	1971	N.H. Pillsbury
Last Bridge	Approx. 3	Q, SSC	1971	N.H. Pillsbury

[1] CS = continuous stage; MS = manual stage; Q = discharge rate; CNTU = continuous turbidity; MNTU = manual turbidity; SSC = suspended sediment concentration; CWT = continuous water temperature; FV = float velocity.

[2] USGS = US Geological Survey; RSL = Redwood Sciences Laboratory; RK = R. Klein; SF = Salmon Forever/Watershed Watch; HSUE = Humboldt State University Engineering; NM = N. Murano.

COMPONENTS OF A SEDIMENT BUDGET FOR JACOBY CREEK

Erosion and Sediment Delivery

At present, erosion and sediment delivery are the least well-known of the components of a sediment budget for Jacoby Creek, although several reports speak indirectly to these processes. A basin-wide erosion inventory would be the best method for determining erosion and sediment delivery rates and volumes. This would involve field sampling and air photo analyses to estimate erosion volumes by process, age (timing) and cause. Such an inventory was done for the Van Duzen River watershed a few years ago (PWA, 1999). However, depending on the time frame of interest, some older erosion features may not be visible on the ground. For example, small gullies, rills, and surface erosion features disappear with several years of inactivity due to leaf litter accumulation and vegetation growth, and are typically not discernable from field inventories. The cost of this type of inventory, along with private property issues, may make this infeasible.

A less expensive alternative would be to perform an air photo landslide inventory to determine landslide void and delivery volumes, and timing. This is a fairly straightforward method that has been widely applied in coastal northern California and elsewhere. While this would capture the larger erosion features on the landscape, smaller landslides, gullies, and surface erosion often cannot be seen and thus quantified in forested terrain using air photos. In this case, one would have to rely on applying erosion rates measured elsewhere in an area with similar climate and geology. Fortunately, there are several research areas where erosion measurements have been taken that could potentially provide data suitable for application to Jacoby Creek (e.g., Caspar Creek, Van Duzen River, Redwood Creek).

Sediment Storage

Sediment storage in Jacoby Creek is likely to be concentrated in alluvial reaches; those with low gradient with bed and banks composed mostly of gravel and smaller sediments; such reaches are commonly termed ‘storage reaches’. Other reaches that are steeper and bedrock-dominated are not likely to store much sediment; these are referred to as ‘transport reaches’ because most sediment routed to such reaches is quickly transported through them to downstream areas. There are at least two reaches of significant length along the main channel that are considered alluvial and capable of storing relatively large volumes of sediment. The most obvious is the lowest reach of Jacoby Creek that extends from the mouth upstream to the valley head (near South Quarry Road). Another is located in the upper main channel near the former USGS gaging station now operated by RSL. Other alluvial stream reaches capable of storing appreciable sediment volumes undoubtedly exist, but are shorter in length.

In steeper reaches of Jacoby Creek, significant sediment storage can occur upstream of log jams or road crossings. Such features create a local ‘base level’, a natural or artificial rise in the streambed elevation that lowers the gradient upstream, creating conditions conducive to sediment deposition and storage. In steeper reaches, the influence of a local base level extends a relatively shorter distance upstream than in gentler reaches. When a log jam fails or a stream crossing fails or is altered, all or a portion of the sediment previously stored upstream can be rapidly transported downstream as the channel incises through the sediment.

As mentioned earlier, numerous channel cross sections exist in Jacoby Creek and have been surveyed at various time periods. A suite of cross sections was established in 1989 by RSL between the South Quarry Road and Brookwood bridges. These were surveyed initially in 1989, and then re-surveyed in 1990 and, most recently, many were re-surveyed in 2003 (some could not be re-surveyed due to denial of access by landowners). In addition, Dr. Andre Lehre of HSU established six cross sections in 1992 that bracket the Brookwood Bridge. Most or all of these were re-surveyed in 1995, 1997, 2001, 2002, and 2003.

A second reach where cross sections have been surveyed is upstream of the upper Jacoby Creek gaging station. RSL has established 23 cross section in that reach. From surveys conducted in 2002 and 2003, the effects of the stream channel cutting around a log jam were observed. Scour was observed in the upstream cross section (those above the log jam) while fill (deposition) was observed downstream (S. Hilton, RSL, pers. comm.).

While the upstream cross sections document the effects of a change in local base level (due to the stream cutting around a log jam), the downstream cross sections exhibit a decade-long trend of aggradation. Cross sections in the Brookwood reach uniformly showed sediment deposition of approximately one to two feet on average from the early 1990s though 2003, though quantitative cross section analysis has not yet been done. The more frequently surveyed Lehre cross sections indicate that most of this aggradation occurred between 1995 and 2001 (see Fig. 2), with minor amounts of additional aggradation since 2001. Of note, many of Lehre's cross section endpoints have become buried by sand and silt-sized sediment, requiring a metal detector to relocate and excavate them for re-survey. This contrasts with material within the channel bed, where material deposited is in the fine to coarse gravel size range.

The Brookwood Bridge was built in 1967 and ownership was transferred from the subdivision developers to Humboldt County in 1969. The County Public Works Department occasionally contracts out bridge assessments to local engineers, and these reports often include photos and 'bridge soundings' (measuring the depth from some point on the bridge down to the channel bed) that can be used to track channel changes through time. A bridge assessment was done in 1973 that included soundings, and these were re-done by me in 2004 (see Fig. 3). Although based on just a few points on the channel bed from 1973, it appears that the changes from 1973 to 2004 are about the same as those from 1992-2004 (Fig. 3), indicating that the channel bed was probably stable from 1973 through 1992, with instability in the form of aggradation beginning in the mid-1990s and continuing through the present. However, it appeared the 1973 soundings were only recorded to the nearest foot, so some error is expected in the comparison.

Consistent with the cross section story, I have observed visual evidence of recent aggradation elsewhere, both above and below the Brookwood cross section reach. Many low-growing trees have their bases buried by recent sediment deposition on lower banks (silt and sand) and the channel bed (gravel and cobble). Aggradation is apparently affecting virtually the entire lower reach of Jacoby Creek from valley head to Arcata Bay.

The combination of cross sections and other methods of quantifying sediment storage should provide a fairly reliable basis for quantifying changes in sediment storage for the past decade or so, but will require field analysis (using tree burial, sediment cores, etc.) to provide a more spatially complete data set than that provided solely by the cross sections.

Figure 3. Jacoby Creek at upstream side of Brookwood Bridge (Lehre XS 3)

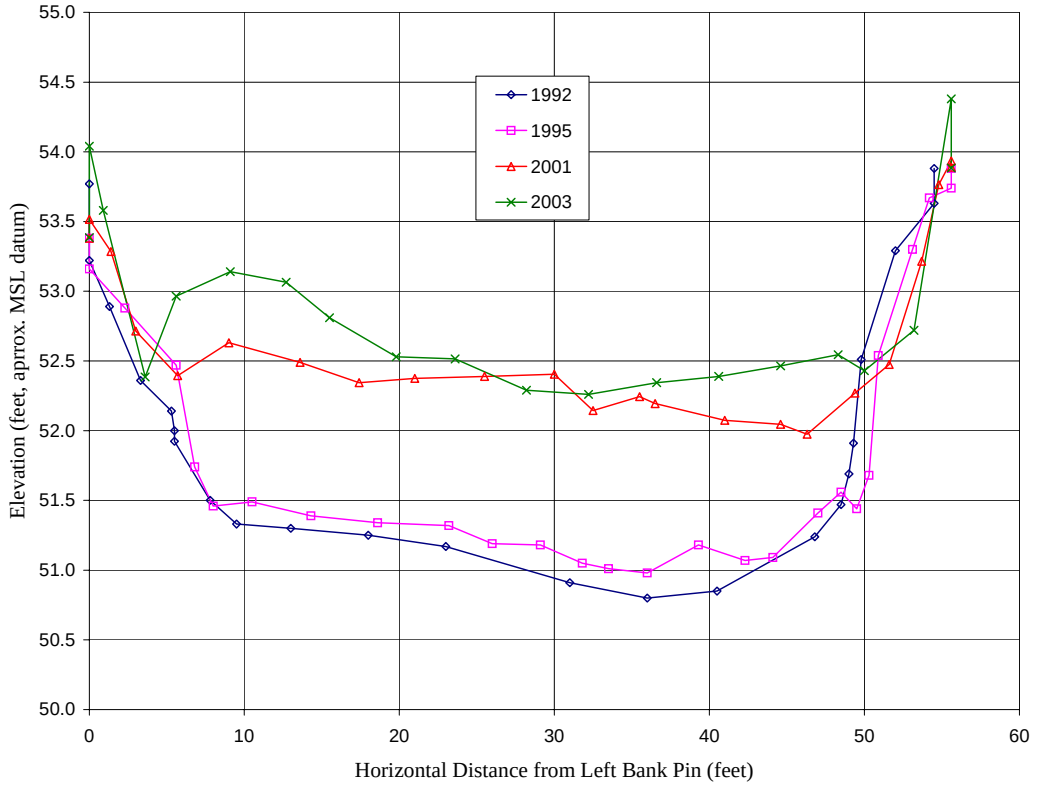
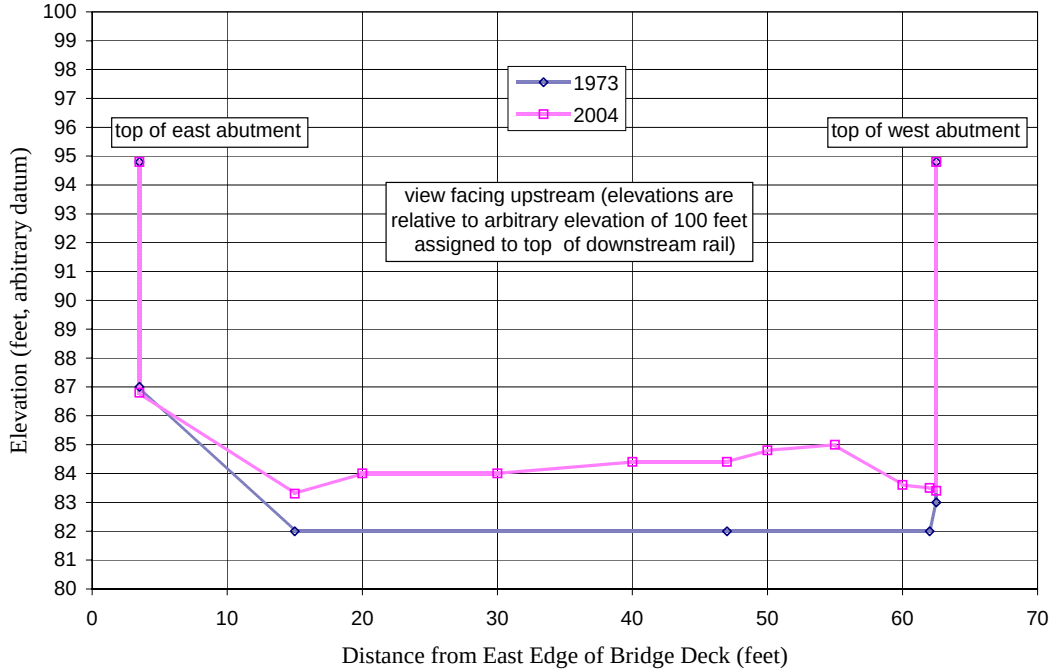


Figure 4. Brookwood Bridge soundings, 1973 and 2004, downstream side
(1973 by W. Langenbach; 2004 by R. Klein)



Sediment Yield

The two continuous stream gaging stations in Jacoby Creek provide data that can be used to quantify sediment yield in recent years. The use of recorded turbidity, in combination with laboratory analysis of water samples for suspended sediment concentration and water discharge, allows relatively accurate determination of suspended sediment discharge. Earlier monitoring at the Brookwood site by RSL (1978-84) provides bedload transport rates as well as suspended sediment and discharge data that may be useful for estimating total sediment yield. However, the records are not continuous and thus would not provide sediment yield estimates that are as accurate as those for the later continuous recording period. For the earlier monitoring period at the upper gaging station (1955-74), only stream discharge was recorded, thus no sediment yield estimation is possible. However, more recent monitoring (2000-present) includes continuous discharge and turbidity and stormflow sampling for suspended sediment, allowing accurate suspended sediment estimation for the upper gaging station.

While the basic data exists for sediment yield estimates for recent years, not all of it has been prepared for sediment yield computation. This requires several steps: 1) correction of spurious turbidity data, 2) development of turbidity (NTU) to suspended sediment concentration (SSC) relationship, 3) calculation of discharge from stage, and 4) integration of discharge with SSC to estimate suspended sediment yield. Several of these tasks are laborious and time consuming, consequently not all estimates have been completed. I have made a preliminary computation of suspended sediment yield for lower Jacoby Creek for water year 2003 (winter of 2002-2003) that is 12,500 tons, or 1,136 ton/mi^2 for the 11.0 mi^2 watershed draining to the former site above South Quarry Road (see Fig. 4). For the present water year (winter, 2003-2004), it is forecast that suspended sediment yield will likely be only about one-third of that (about 4,200 tons, see Fig 5) due to lower stormflows.

Figure 5. Discharge, turbidity, and suspended sediment yield for Jacoby Creek at South Quarry Road, Water Year 2003

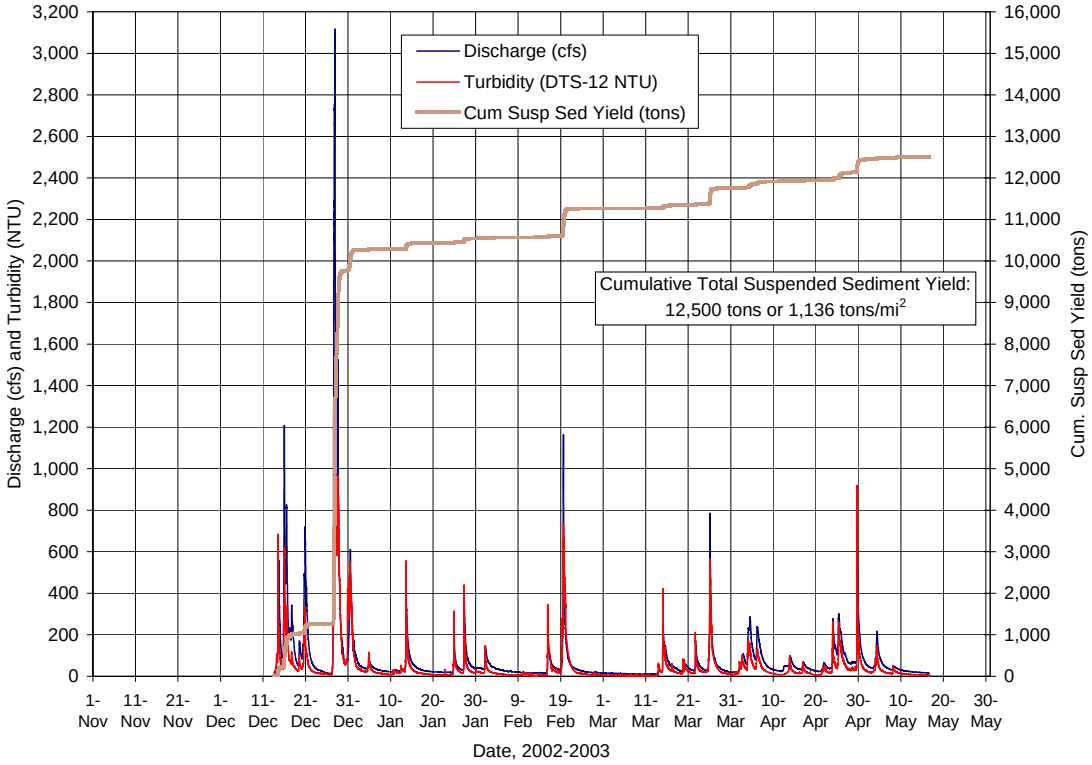
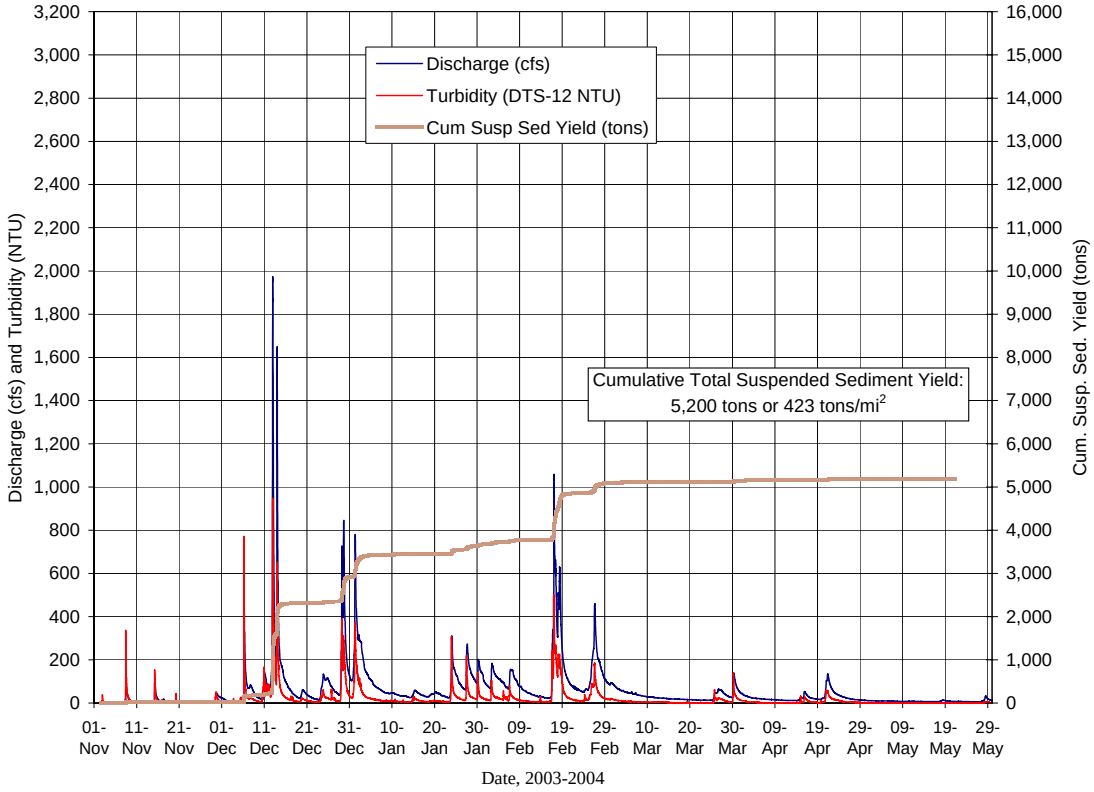


Figure 6. Discharge, turbidity, and suspended sediment yield for Jacoby Creek at Brookwood Bridge, water year 2004 (preliminary[1]).



When suspended sediment yields are computed for the upper gage, they can be compared with those from the lower gage to evaluate differences in sediment yields between the upper and lower portions of the basin. In addition, the partial record stations provide information at a somewhat finer scale, allowing relative inputs of suspended sediment from major tributaries to be characterized.

Two master's theses written in the 1970s focussed on suspended sediment and turbidity in Jacoby Creek. Johnson (1972) performed limited turbidity and discharge sampling in four tributaries to examine the effects of logging, but sampling was only done during low flow conditions in late-winter and spring, 1969. Nonetheless, some large differences were detected that showed increased turbidity after logging and road-building conducted in the 1960s (before the modern Forest Practice Rules wen into effect). Perhaps the most informative aspect of this study was the documentation of logging-related damage with photographs and text. In-channel landings, inner gorge roads, inadequate road drainage, and tree removal on very steep, unstable slopes caused extreme erosion and sediment delivery that undoubtedly affects even the present-day sediment budget.

A much more intense suspended sediment and discharge data collection effort was undertaken by Pillsbury (1972) in Jacoby Creek (listed in Table 5). He sampled at 11 sites (five primary sampling sites and six minor sampling sites) during 11 storms from January through April, 1971. Enough samples were taken at most sites to construct suspended sediment rating curves. Although most storms were only sampled once, multiple measurements of discharge and suspended sediment concentration were taken during one storm (March 22-24) to characterize much of the storm's hydrograph. Several of Pillsbury's sites coincide with more recent sampling: the upper gaging station now operated by RSL, Morrison Gulch, and the main channel near South Quarry Road (called 'the Smart property' in the thesis). Unfortunately, the latter site was classified as a 'minor' sampling station, and data from these stations was not included in the thesis appendices. As with the Johnson (1972) thesis, the Pillsbury (1972) thesis included photos and text describing extensive erosion and sediment delivery.

SUMMARY AND RECOMMENDATIONS

Although a great deal of information exists that will useful for constructing a sediment budget for Jacoby Creek, it was not originally collected for this purpose. Consequently, the information is spotty, but this is almost always the case with sediment budgets. Moreover, sediment budgets are commonly constructed using less site-specific information than exists for Jacoby Creek.

Although not essential, use of a geographic information system (GIS) is recommended as a tool for aiding in constructing the sediment budget for Jacoby Creek. Some of the information (e.g., slope steepness, post-1988 timber harvest, land ownership, geology, etc.) already exists in GIS format, while other layers (e.g., road systems, landslides, etc.) would have to be digitized before GIS analysis. More sophisticated analyses can be performed using GIS, and the data can be readily updated for incorporating future changes in the watershed.

The following lists tasks for constructing a sediment budget for Jacoby Creek and options for completing some tasks. Very approximate costs are provided for Tasks 3-5.

Task 1: Articulate clear key questions and goals for the sediment budget. The goals and objectives must be set to match the intended user of and uses for the sediment budget. This critical first step will help determine the focus for filling data gaps in terms of the time period, data quality, causal relationships, and other issues. This exercise should include developing a list of key questions, such as "what is the relative importance of roads in sediment delivery?", "what is the relative importance of current timber harvesting versus legacy effects from past harvesting?", and "how large a contribution to

sediment delivery do residential roads make?" Answering questions like these at the outset will improve the ability of the sediment budget to meet the intended goals in the most cost-efficient way.

Several possible questions are listed below for consideration:

- What erosion processes and possible relationships to past and present land use explain the recent aggradation in the lower main channel and high suspended sediment loads?
- What are the relative magnitudes of erosion and sediment yields caused by land uses and which areas within the watershed are most vulnerable to disturbance-driven erosion and sediment delivery?
- What are the most cost-effective methods to reduce current and future sediment threats within the watershed?
- Are fish-bearing channels in a condition to derive benefits from instream restoration, and if so, where and how should it be done?

There are existing data and reports capable of addressing several of these questions (e.g., PWA 2003), but they do not cover the entire watershed nor do the address the full range of issues (e.g., residential development effects, ongoing timber harvest).

Two likely goals for a Jacoby Creek sediment budget will be to help set priorities for watershed protection and restoration and to support the eventual completion of a sediment TMDL (total maximum daily load) analysis for the watershed (although Jacoby Creek has been listed as 'sediment impaired', a date has yet to be set for the TMDL). Other goals may also be developed, but stakeholder input will be required to ensure they are appropriate and achievable.

Task 2: Select the time period for which the sediment budget will be constructed. The time period for which a sediment budget is developed determines the specific data sets that must be developed for analysis. Data availability will constrain the time period selected. For example, although the air photo record for inventorying large landslides is lengthy, the period for which sediment yield can be determined is much shorter. For some variables, data can be synthesized to extend the record, but such estimates will not be as reliable as those based on observations.

The maximum time period will be the period covered by air photos suitable for inventorying large erosion features and land use history (timber harvesting and road building, residential development). Although this would be useful for characterizing long term conditions, a shorter period may suffice as long as it encompasses erosion and sediment delivery events that may still be affecting water quality and channel conditions.

Task 3. Determine Sediment Yield (estimated cost = $5,000). Suspended sediment yield is known or can be determined from data collected at the two continuous stream gaging stations on the main channel for recent years. Relative to other components of the budget, suspended sediment yield for the years when recording data on discharge and turbidity were collected (since 2000 at the upper gage, and since 2003 at the lower gage) will be the most accurate. Suspended sediment yield can be estimated for other years using synthesized data, but the accuracy will be diminished.

Although several other non-recording stations exist, they cannot be used for estimating annual suspended sediment yield. However, these stream monitoring stations may be useful for shedding light on the geography of primary sediment source areas. While Morrison Gulch has an active streamflow gaging station, suspended sediment sampling has been spotty and there is no recording turbidity sensor. However, the suspended sediment rating curve method (using discharge as a surrogate for suspended

sediment concentration) should be investigated as a possible method for estimating recent suspended sediment yield for the tributary.

Bedload sediment yield can be estimated using transport rates from measurements taken at Brookwood Bridge in the 1980's and in 2004 by RSL, assuming enough samples were obtained to construct a rating curve.

Task 4: Determine Changes in Stored Sediment (estimated cost = $10,000). Recent increases in channel-stored sediment are known through monitoring of channel cross sections in two relatively low gradient reaches of the main channel: one reach of the upper main channel (near the gaging station operated by RSL) and another in the lower channel near Brookwood Bridge. Since these are the primary storage reaches in Jacoby Creek, much can be said about channel sediment storage changes from these data. Field investigations relying on evidence of recent channel bed and bank changes (e.g., tree root crown burial, sediment cores from the channel bed and banks, etc.), are needed for determining recent storage changes elsewhere in Jacoby Creek.

Task 5: Estimate Erosion and Sediment Delivery (estimated cost = $30,000). The most limiting aspect of existing data for a sediment budget is the lack of erosion/sediment delivery inventories and monitoring. Although some generalities are known, for example, erosion processes operating on the northern slopes are dominated by slump earthflows, while debris slides dominate the southern slopes, quantitative information on erosional history and current conditions is required to construct a sediment budget. An air photo-based landslide inventory with ground-truthing would provide basin-specific data on this undoubtedly primary component of erosion in Jacoby Creek. Such an inventory should not be too expensive given the small size of the basin (see cost estimate, above). The air photo record for Jacoby Creek appears to be sufficient for a landslide inventory spanning the past five or six decades.

As mentioned earlier, PWA (2003) inventoried much of the forest road network with the objective of identifying and prioritizing potential (i.e., future) road erosion and sediment delivery sites. While this is an important first step in assisting long term channel recovery, it is not useful for constructing a sediment budget that focuses on past sediment delivery.

A ground-based inventory, focusing on the road system and especially vulnerable hillslope areas, could provide much information on other erosion processes and features, such as smaller landslides (especially those occurring beneath the forest canopy and thus not visible in air photos), road-related erosion, recent surface erosion, rilling and gullying. A sampling method similar to that used in the Van Duzen River watershed (PWA, 1999) could be employed to save money relative to a complete inventory.

Although a basin-wide, ground-based erosion inventory may not be cost prohibitive if a proper sampling strategy is used, access to private lands may prove to be a major limitation. If so, erosion and sediment delivery processes (e.g., small landslides, gully and rill erosion, sheetwash), that cannot be discerned from air photos will have to be estimated using data from other similar northcoast streams. The most obvious candidates for transferring erosion and sediment delivery data would be Caspar Creek in Mendocino County (a research watershed for CDF and RSL), and the Van Duzen River (using values from the PWA 1999 study), making adjustments where applicable to account for differences in slope, geology, soils, land uses, etc.

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