# SEDIMENT BUDGET STRATEGY FOR HUMBOLDT BAY WATERSHEDS, 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 watershed draining to Humboldt Bay in Humboldt County, California. Key tasks for this strategy were:

- 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 considerable amount of information exists that describes the tributaries that drain to Humboldt Bay, more than can be mentioned or summarized in this report. However, the most relevant sources of material specifically relevant to constructing a sediment budget have been incorporated to the extent feasible.

Costa and Glatzel (2002) report the entire watershed area of Humboldt Bay to be about 223 $mi^2$, with about 25 $mi^2$ composed of the bay itself at high tide. Subtracting the bay area from the total area gives an estimate of about 198 $mi^2$ as land surface area draining to the bay. Several relatively large streams and smaller named tributaries drain to Humboldt Bay are shown in Table 1, listed from north to south.

Table 1. Named tributary streams to Humboldt Bay and their approximate drainage areas.

| Stream | Drainage Area (approx. $mi^2$) |
|---|---|
| Janes Creek | 4 |
| Jolly Giant Creek | 1 |
| Grotzman/Beith Creek | 2 |
| Jacoby Creek | 19 |
| Washington Gulch | 1.3 |
| Rocky Gulch | 1.6 |
| Freshwater Creek | 34 |
| Ryan Creek | 15 |
| Elk River | 53 |
| Salmon Creek | 18 |
| **Total** | **149** |

These ten watersheds total about 149 $mi^2$, thus the remaining lands draining to Humboldt Bay account for an additional 49 $mi^2$, consisting of former tidelands, floodplains and small, unnamed tributary watersheds. Figure 1 shows the larger watersheds. Humboldt Bay is unique on the west coast because of it's relatively low ratio of land area to bay area (about 8). This factor has major implications for the sediment budget, as the source area for sediment delivery to the bay is relatively small, limiting the potential for sedimentation relative to other bays that have large rivers draining through them. Partially negating this, however, is the unusually high erodability of the uplands surrounding Humboldt Bay, causing higher unit sediment delivery rates (e.g., tons per square mile) than most other large west coast embayments.

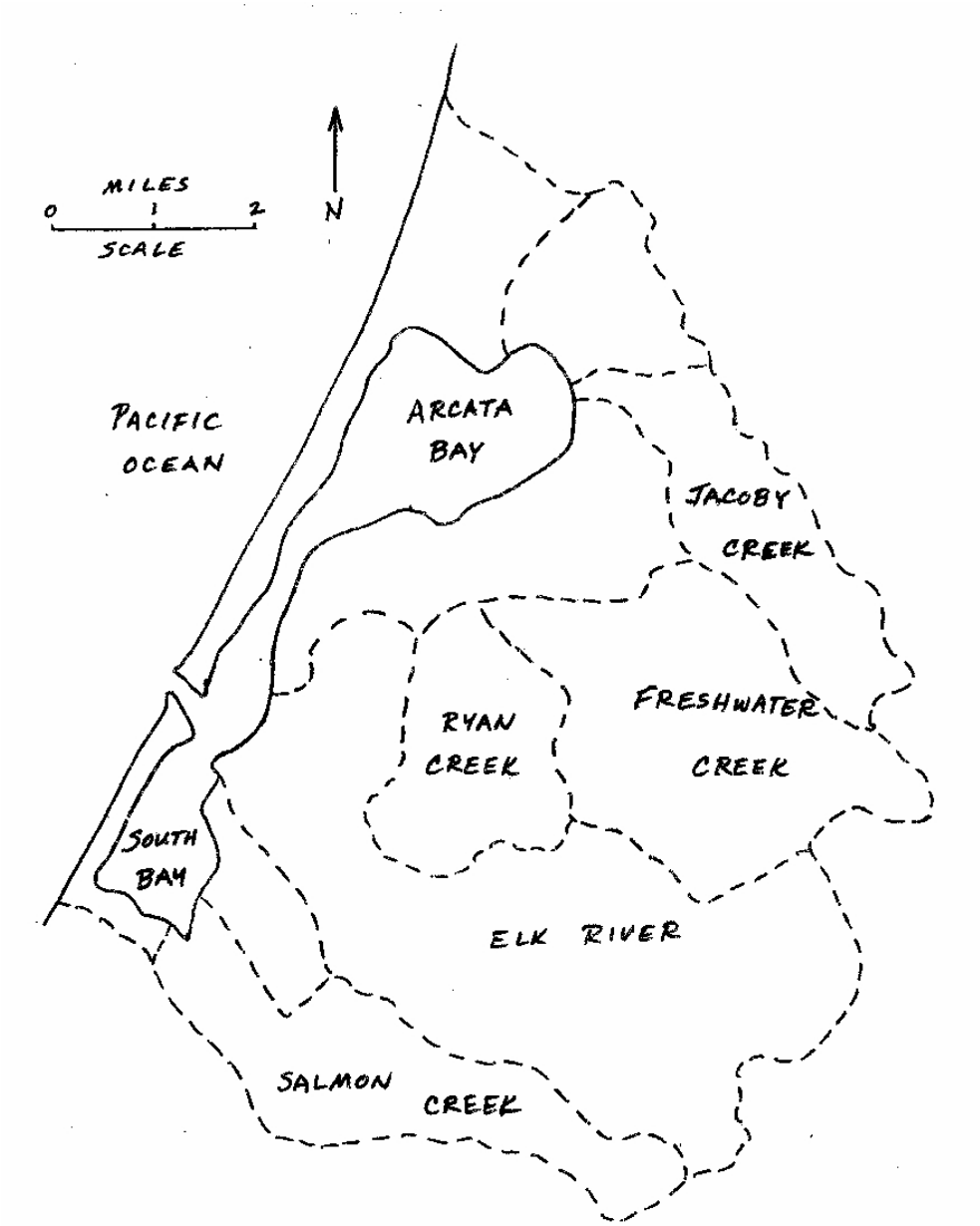



Figure 1. The Humboldt Bay watershed showing major tributaries.

In Jacoby Creek, about 80% of the watershed area consists of uplands (mostly timbered hillslopes) and the rest of low gradient pasture, wetlands, rural residential lands and urbanized lands located on floodplains and terraces. Assuming this same percentage for all lands surrounding Humboldt Bay, about 160 $mi^2$ of uplands and about 40 $mi^2$ of lowlands drain to Humboldt Bay. Most of the lowland areas are separated from streams and the bay by earthen levees. The cities of Eureka and Arcata comprise the main urbanized areas in the watershed, totaling roughly about six square miles.

### *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), '$\Delta$S' 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 Humboldt Bay would 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 Humboldt Bay uplands 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, channel, and floodplain 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.

Sediment storage also occurs on floodplains from overbank flood events, and sediment stored on floodplains typically has very long residence times. However, where channels are leveed, sediment transport and deposition is confined to the channel except when the levees are overtopped. Consequently, lowlands adjacent to the bay are much less of a sediment 'sink' than before levee construction, and the sediment (primarily sand, silt and clay) that would have otherwise deposited on floodplains during relatively frequent overbank floods is instead transported to the bay.

***Geology and Geomorphology***

The Humboldt Bay watershed upland areas comprise the source areas for sedimentation; they are composed of relatively weak rocks and erodable soils on moderately steep to very steep slopes. Landslides are common, and faults riddle the area and separate areas of uplift from adjacent areas of tectonic subsidence. While a detailed description of the geology and geomorphology of the Humboldt Bay watershed was beyond the scope of this project, several generalizations and information sources are included here.

Geologic conditions in watersheds draining to Humboldt Bay are well-described due to several geologic mapping activities related to development projects, research projects conducted by Humboldt State University professors and students, and inventories performed for timber companies with holdings in the watershed. An often-cited description of geologic conditions around Humboldt Bay is found in Bailey and others (1964) who describe the Franciscan assemblage that dominates the area. Carver and Stephens (1985) mapped the geology of two quadrangles in the Humboldt Bay region (Arcata South and Korbel). Lehre and Carver (1985) examined landsliding in Jacoby Creek, its relationship to geology and geomorphology, and its role in the long term sediment budget for the watershed. Ogle (1953) describes another important geological component within the southern portion of the Humboldt Bay watershed, the Wildcat Group, consisting primarily of siltstones and mudstones. This unit is correlative with the Falor Formation, also composed of sedimentary rocks (Carver, 1987). These are just a few of the many sources of information on Humboldt Bay's geology and geomorphology.

A sediment budget for Humboldt Bay would rely, in large part, on a thorough understanding of the geology and geomorphology of the area because of their roles in determining the natural rates of erosion and sediment delivery and the susceptibility of hillslopes to increased erosion from land use. In addition, an erosion inventory that relies on representative sampling (a necessity in terms of cost feasibility) would benefit from a stratified sampling approach that takes geology and geomorphology into account.

### *Land Use*

Hillslopes within the Humboldt Bay watershed 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 bottoms, but also exists in some steeper areas and along several ridges. 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.

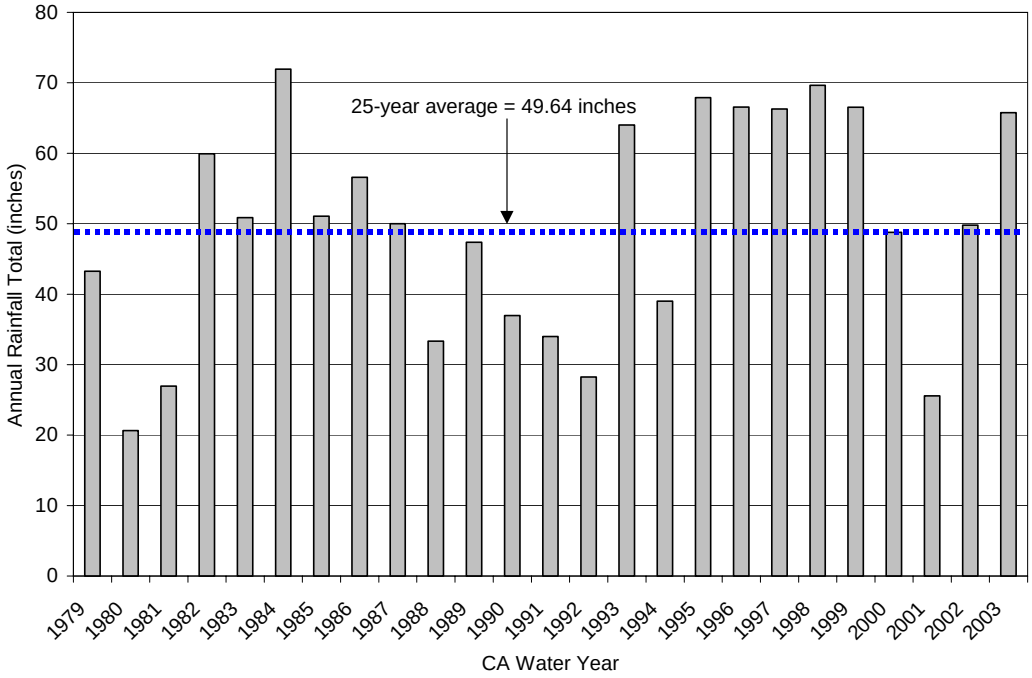
Land use is well documented in coastal northern California and elsewhere as a potentially large contributor to elevated erosion and sediment yield. Residential developments can contribute to surface erosion primarily during construction if vegetation clearing and earthmoving occur. Access roads to residential 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. Several long-term recording rain gages exist in or near the Humboldt Bay watershed with the longest continuous record provided by the National Weather Service in the City of Eureka.

Although rainfall varies substantially with elevation in the watershed, 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). Rainfall at these two locations likely characterizes the range of conditions in the larger Humboldt Bay watershed, although other rainfall data are collected at numerous other locations with shorter record lengths that could be useful for determining rainfall depths and intensities for specific areas or time periods. For example, 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. 2) is in close agreement with the average of the other two gages.

Figure 2. Annual Rainfall (July-June) for Jacoby Creek Canyon, 1979-2003 (from R. Lewis)

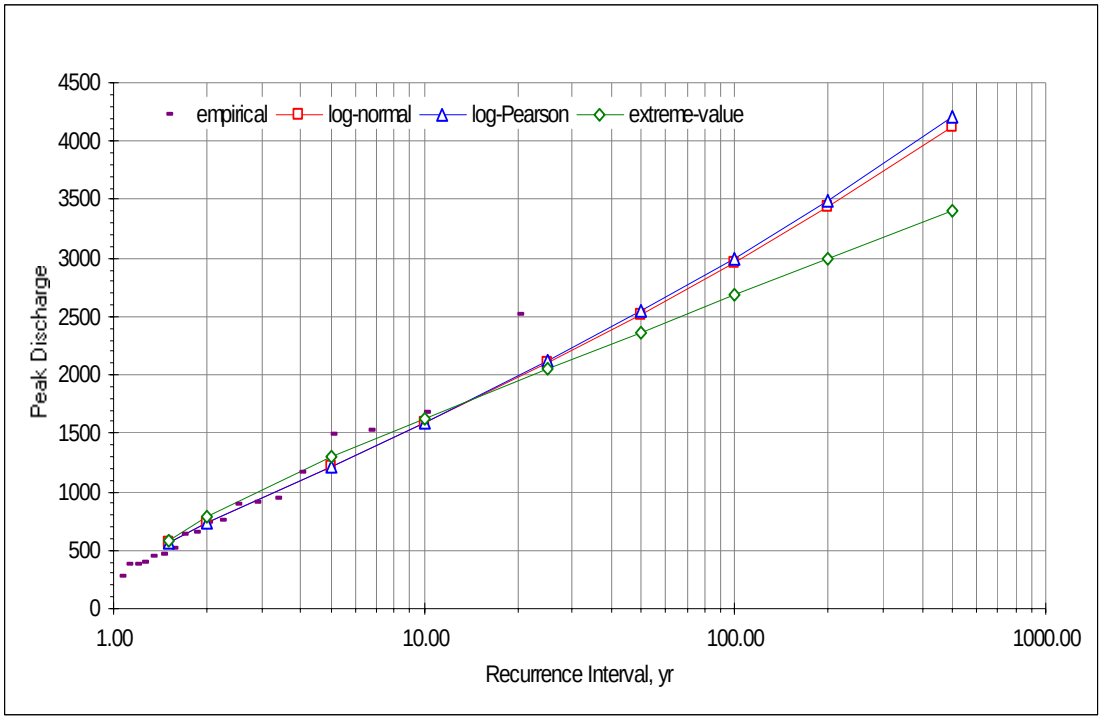



### *Hydrology*

The hydrology of tributaries to Humboldt Bay is typical of small, coastal drainages, characterized by extremes. Winter storm peaks are typically rainfall-driven, with snowmelt playing an insignificant role. This contrasts with larger basins extending farther inland and higher in elevation, where snow accumulation can play a dramatic role in floods (e.g., the 1964 flood). Peak flows in Jacoby Creek, for example, can exceed 500 cfs per square mile, while low summer flow can get as low as 0.1 cfs per square mile, and perhaps lower. Other Humboldt Bay tributary watersheds likely have similar flow regimes.

A stream gage in upper Jacoby Creek has the longest period of record of any stream in the Humboldt Bay watershed (1955-74 by the USGS, and 2000-present by Redwood Sciences laboratory). Lehre and Carver (1985) estimated mean annual discharge for the upper third of the watershed (using the USGS data record from this gage, No. 11-4800, drainage area = 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 3 shows flood frequency curves developed for the upper Jacoby Creek 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 or mean annual flow between the gage location and the point of interest.

Figure 3. 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).




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.

Table 2 lists all known continuous hydrologic monitoring previously or presently conducted in Humboldt Bay tributaries. As indicated, there exists a fair amount of information on stream discharge, turbidity and SSC 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 continuous (automated) turbidity recording stations (there are 22 such stations listed in Table 2), as continuous data sets allow relatively accurate estimates of sediment yield to be developed. Stations with continuous discharge and manual suspended sediment sampling can also provide estimates of suspended sediment yield, but with less accuracy. Salmon Creek (drainage area = 18 $mi^2$) is the largest ungaged tributary to Humboldt Bay, consequently, no information exists on sediment yield for this large tributary to the South Bay.

Table 2. Continuous recording hydrologic monitoring sites in the Humboldt Bay watershed

| Location | Drainage Area ($mi^2$) | Data Collected[1] | Period of Record | Operator[1] |
|---|---|---|---|---|
| **Jacoby Creek** | | | | |
| Upper Jacoby Creek | 6.1 | CS, Q, CNTU, SSC | 2000-present | RSL |
| South Quarry Road | 11.0 | CS, Q, CNTU, SSC | 2002-2003 | RK |
| Brookwood Bridge | 12.3 | CS, Q, CNTU, SSC | 2003-present | RK |
| Morrison Gulch | 1.0 | CS, Q, MNTU, SSC | 2002-present | HSUE |
| **Janes Creek** | | | | |
| Janes Creek at Spear Ave. | 3.0 | CS, Q, MNTU | 2000-2001 | JA&RK |
| Janes Creek at 17th Street | 3.5 | CS, Q, MNTU | 2000-2001 | JA&RK |
| Janes Creek at Arcata Bay | 4.0 | CS | 2000-2001 | JA&RK |
| **Jolly Giant Creek** | | | | |
| Jolly Giant Creek at K Street | 0.8 | CS, Q | 2001-present | MB&T |
| **Rocky Gulch** | | | | |
| Rocky Gulch at D. Mireau's | 1.6 | CS, Q | 2002-present | DM |
| **Freshwater Creek** | | | | |
| Freshwater Cr. at T Roelofs | 12.6 | CS, Q, CNTU, SSC | 2000-present | SF |
| Freshwater Cr at Incline A | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| Freshwater Cr at Incline B | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| Freshwater Cr at Incline C | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| SF Freshwater Creek | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| Graham Gulch | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| McReady Gulch | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| Cloney Gulch | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| **Ryan Creek/Slough** | | | | |
| Ryan Creek | 15 | CS, Q, CNTU, SSC | 2003-present | GDC |
| East Fork Ryan Cr. | unknown | CS, Q, MNTU, SSC | 2003-present | GDC |
| West Fork Ryan Cr. | unknown | CS, Q, MNTU, SSC | 2003-present | GDC |
| Guptil Creek | unknown | CS, Q, MNTU, SSC | 2003-present | GDC |
| **Elk River** | | | | |
| North Fork Elk at Wrigley Orchard | 22.4 | CS, Q, CNTU, SSC | 2001-present | SF |
| NF Elk at Trend Sta 14 | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| NF Elk at Mill Creek | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| Main Stem Elk at fmr USGS site | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| Bridge Cr (in NF Elk) | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| South Branch NF Elk | unknown | CS, Q, CNTU, SSC | 2003-present | PM |
| Corrigan Creek (in SF Elk) | unknown | CS, Q, CNTU, SSC | 2003-present | PM |
| Little South Fork in Old Growth | unknown | CS, Q, CNTU, SSC | 2003-present | PM |
| South Fork Elk at M. Bohannen's | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| South Fork Elk | unknown | CS, Q, CNTU, SSC | 2002-present | PL |
| South Fork Elk at Rockpit | unknown | CS, Q, CNTU, SSC | 2002-present | PL |

[1] CS = continuous stage; Q = discharge rate; CNTU = continuous turbidity; MNTU = manual turbidity; SSC = suspended sediment concentration;

[2] USGS = US Geological Survey; RSL = Redwood Sciences Laboratory; RK = R. Klein; SF = Salmon Forever/Watershed Watch (note, only continuous recording stations are listed; SF also maintains several manual stations); HSUE = Humboldt State University Engineering; PL = Pacific Lumber Co. (note, only continuous recording stations are listed; PL also maintains several manual stations); JA&RK = J. Anderson and R. Klein; GDC = Green Diamond Co. (note, only continuous recording stations are listed; GDC also maintains several manual stations); MB&T = McBain and Trush Co.; DM = D. Mireau; PM = Peter Manka (HSU CNR)

## COMPONENTS OF A SEDIMENT BUDGET FOR HUMBOLDT BAY

### *Erosion and Sediment Delivery*

At present, erosion and sediment delivery are the least well-known of the components of a sediment budget for the Humboldt Bay watershed. although erosion inventories have been performed in parts of two of the larger watersheds; North Fork Elk River and Freshwater Creek (PWA, 1998; PWA 1999a). A basin-wide erosion inventory would be the best method for determining erosion and sediment delivery rates and volumes. This would include 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, 1999b). 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 Humboldt Bay tributary watersheds 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. The larger tributaries contain reaches of significant length along the main channel that are considered alluvial and capable of storing relatively large volumes of sediment. In Jacoby Creek, for example, the most obvious storage reach is the low gradient reach 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 likely shorter in length.

In steeper, ‘transport’ reaches, significant sediment storage typically only occurs upstream of log jams or road crossings because they local ‘base levels’, a natural or artificial rise in the streambed elevation that lowers the gradient upstream, creating conditions conducive to sediment deposition and storage. In such 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.

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, with minor amounts of additional aggradation since 2001.

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. 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, 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, recent aggradation is evident throughout the lower reach of Jacoby Creek. 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 Jacoby Creek example is not typical of other Humboldt Bay tributaries, having been the focus of scientific research. Surveyed cross sections and bridge soundings also provide information on channel storage in other Humboldt Bay tributary watersheds, however, they are fewer in number and generally not surveyed very frequently. For example, several streams (Freshwater Creek, Janes Creek, Jolly Giant Creek) have had detailed flood analyses performed in their lower reaches for floodplain delineation by Federal Emergency Management Agency (FEMA) contractors. Although these cross sections were not intended for monitoring, they can, in some cases, be relocated and resurveyed to examine channel storage changes, and some have (e.g., lower Freshwater Creek). In addition, bridge inspection records are maintained by the Humboldt County Department of Public Works, which contain occasional 'soundings' (depth measurements from some part of the bridge to the channel bed) and photos that could also be useful for evaluating channel bed changes (as with the Jacoby Creek Brookwood Bridge data mentioned above). The combination of cross sections and other methods of quantifying sediment storage could provide a basis for quantifying changes in sediment storage, but will require field analysis (using tree burial, sediment cores, etc.) to provide a more spatially complete data set than that provided solely cross sections or bridge soundings.

### *Sediment Yield*

The continuous recording stream gaging stations listed in Table 2 provide data that can be used to quantify suspended 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. Other non-recording stations could also provide information for quantifying suspended sediment yield, but with less accuracy.

Sediment yield, however, is composed of both suspended sediment and bedload. Bedload is typically 10-20% of total load, but the percentage can vary from stream to stream or year to year for a particular stream. Of the Humboldt Bay tributary watersheds, only Jacoby Creek has had bedload sampling. Earlier monitoring in Jacoby Creek 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. Beginning in 2003, bedload sampling at Brookwood Bridge was re-initiated. In the absence of bedload sampling in other Humboldt Bay tributaries, reasonable estimates could be made by applying the contemporary percentage of bedload to suspended load from Jacoby Creek to other suspended sediment monitoring stations with similar characteristics (e.g., slope, drainage area).

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. When suspended sediment yields are computed for the continuous suspended sediment stations, fairly accurate comparisons of suspended sediment yields will be available for a relatively large number of source areas in the Humboldt Bay watershed. In addition, suspended sediment yields can be roughly estimated for the manual sampling, continuous streamflow recording stations using the sediment rating curve approach for those where the relationship between suspended sediment concentration and discharge is relatively strong.

***Humboldt Bay Sedimentation***

Thompson (1971) measured erosion and deposition rates at seven areas of Arcata Bay, all of which were located on high tidal flats. The measurement period spanned just under three years. In two of the seven sites significant net deposition was observed, and tow others experienced net erosion. The other three sites had no or negligible net change. The highest deposition (5.0 cm) occurred near the mouth of Jacoby Creek and indicates an annual rate of 1.8 cm/year, however, the seasonal distribution of accumulation suggests the greatest rates of deposition occur during low flow periods (summer and fall), out of synch with periods of high sediment contributions from terrestrial sources (e.g., the Jacoby Creek watershed). Thompson attributes this to seasonal changes in prevailing wind direction, where strong southerly winds during the winter causes wave-induced erosion due to the long fetch (the distance wind travels uninterrupted across the water surface: the longer the fetch, the greater the wave height for a given wind speed). Conversely, he reasons, during other times of the year, northerly wind prevail and the shorter fetch results in less wave energy for erosion in Arcata Bay. Thompson also suggests that algal mats that cover much of the tidal flat during the spring and summer seasons may add to the apparent sediment accumulation during these times. These hypotheses have not yet been examined by more detailed or longer-term measurements that would be needed to characterize the diversity of depositional and erosional environments in Humboldt Bay.

Thompson (1971) also suggested that the modern-day sediment budget for Humboldt Bay appears to be in dynamic equilibrium, i.e., inflows and outflows are in balance to the extent that they compensate for eustatic sea level rise and ground subsidence rates. Although no measurement of sediment contributions from upland sources were available at the time, Thompson estimates values based on mean annual water discharge and an assumed sediment concentration of 100 mg/l, resulting in an annual upland sediment input rate of about 90,000 cubic meters/year, or only about 12-14% of the total estimated annual input (dredging volumes were used to estimate the total input), the remainder of the input coming in the bay

from the littoral zone (predominantly Mad and Eel river sediments). He correctly states that these are to be considered 'order-of-magnitude' estimates and should be used with caution.

Borgeld and Stevens (in press) re-visited Thompson's (1971) Humboldt Bay sediment observations thirty years later. They found somewhat coarser sediment sizes within the primary tidal channels of the bay, and a decrease in grain size with increasing elevation and distance from the bay entrance, similar in trend to Thompson's (1971) findings. However, the coarser sediment in tidal channels found in the later study suggests that marine-derived sands and silts are being transported farther up-channel than previously. Deviations of these general trends were noted where tidal channels became constricted (coarsening of sediments due to increased velocities) and where dredging widened tidal channels locally (fining of sediment due to decreased velocities). The source for these sediments is the nearshore littoral zone, whereby sediments discharged from nearby rivers (Eel and Mad rivers) that move along the coast via alongshore transport enter the bay during flood tides and are not fully flushed out on subsequent ebb tides, resulting in net accumulation of marine-derived sediment in the bay.

As with Thompson (1971), Borgeld and Stevens (in press) also sampled sediments on tidal flats. Their results indicate no significant changes in sediment sizes on the tidal flats, suggesting that the processes controlling tidal flat sedimentation have not changed substantially since Thompson's (1971) study.

## SUMMARY AND RECOMMENDATIONS

Although a great deal of information exists that will be useful for constructing a sediment budget for Humboldt Bay, much of 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 Humboldt Bay (see Reid and Dunne, 1996).

Although not essential, use of a geographic information system (GIS) is recommended as a tool for aiding in constructing the sediment budget. 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 sediment budget will be to help set priorities for watershed protection and restoration and to support the eventual completion of sediment TMDLs (total maximum daily load) analysis for the watershed (TMDLs are already underway for Freshwater Creek and Elk River; Jacoby Creek is also listed 'sediment impaired' but TMDL development has yet to be scheduled). 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 for analysis only = $50,000).** Suspended sediment yield is known or can be determined from data collected at the continuous stream gaging stations (Table 2) 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 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. For example, while Morrison Gulch in Jacoby Creek 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 = $250,000).** Recent increases in channel-stored sediment are known at a few locations through monitoring of a sparse network of channel cross sections (densest in Jacoby Creek) and bridge soundings. This task requires some fieldwork to relocate and re-survey FEMA cross sections and update bridge soundings, along with 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.).

**Task 5: Estimate Erosion and Sediment Delivery (estimated cost = $500,000).** The most limiting aspect of existing data for a sediment budget is the lack of erosion/sediment delivery inventories and monitoring. Although some areas have been inventoried, the majority of the Humboldt Bay watershed lacks this key information. An air photo-based landslide inventory with ground-truthing would provide basin-specific data on this undoubtedly primary component of erosion and sediment delivery. Such an inventory should not be too expensive given the small size of the basin (see cost estimate, above). The air photo record 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, 1999b) 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, see USDA, 1998), 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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