Comparison of Estimated and Measured Sediment Yield in the Gualala River[1]

Matthew O'Connor[2], Jack Lewis[3], and Robert Pennington[2]

Abstract

This study compares quantitative erosion rate estimates developed at different spatial and temporal scales. It is motivated by the need to assess potential water quality impacts of a proposed vineyard development project in the Gualala River watershed. Previous erosion rate estimates were developed using sediment source assessment techniques by the North Coast Regional Water Quality Control Board and by the California Geological Survey. Reported in this study is the estimated sediment yield under existing conditions in Soda Springs Creek (1.5 mi^2) based on similar, but modified, techniques. The modified technique incorporated elements of both prior approaches, substituting detailed data for road erosion and adding site specific data for landslides not previously available. This study also reports sediment yields determined by a suspended sediment monitoring program utilizing Turbidity-Threshold Sampling techniques. The monitoring program produced data relating stream turbidity, suspended sediment concentration, and stream discharge during Hydrologic Years (HY) 2006 and 2007. Turbidity and streamflow data collected for HY 2008 to 2011 were used in conjunction with the relationship between turbidity and suspended sediment concentration from HY 2006 to 07 to estimate sediment yields over an additional 4 year period. Measured sediment yields are substantially lower than predicted by sediment source assessment techniques. Variation in geomorphic processes over time and space and methodological problems of sediment source assessments may be responsible for these apparent discrepancies.

Key words: suspended sediment, erosion, water quality, mass wasting, turbidity threshold sampling

Introduction

Water quality in many northern California Coast Range watersheds is designated as "impaired" because of excessive sediment loads. Sediment source assessment (SSA) techniques customarily used to estimate sediment yield in this region require identification of erosion processes and their distribution in the watershed based on field observations and remote sensing data. Erosion rate and sediment delivery to streams are estimated by measuring soil voids such as eroded gullies and landslide scars and by using model algorithms for surface erosion processes and soil creep rates into streams. This approach has been used to estimate both current (impaired) and natural background erosion rates and provide the basis for determining erosion rates expected in a restored watershed. Erosion rates are equated with sediment yield on the assumption that over the long-term they should be in equilibrium. However, time spans required for such equilibrium are unknown and may be many decades.

---

[1] An abbreviated version of this paper was presented at the redwood science symposium, UC Santa Cruz, June 21-23, 2011.

[2] O'Connor Environmental, Inc., POB 794, Healdsburg, CA 95448.

[3] Hydrologic Statistician, 647 Elizabeth Drive, Arcata, CA 95521.

Validation of these estimates can be accomplished by direct measurements of sediment yield.

The Gualala River is listed as having sediment-impaired water quality per provisions of the Clean Water Act Section 303(d).The Gualala River watershed (*fig. 1*) is underlain by Jurassic age sedimentary and meta-sedimentary rocks of the Franciscan assemblage. The San Andreas Fault passes through the western edge of watershed. A substantial portion of the watershed is mantled by active and dormant rock slides and earthflows. The Coast Range is geologically young, and rapid rates of uplift are believed to have contributed to high erosion rates. Watershed studies by the State of California (Klamt et al. 2002) found that historic landscape disturbance caused by logging was severe, and that a trend toward watershed recovery was evident.

Four sub-watersheds located in northwest Sonoma County (*fig. 1*) have been investigated using SSA techniques and the turbidity threshold sampling (TTS) program to measure sediment yield (OEI 2008). Findings for Soda Springs Creek are representative of the three other sites, which are excluded from this report for brevity.

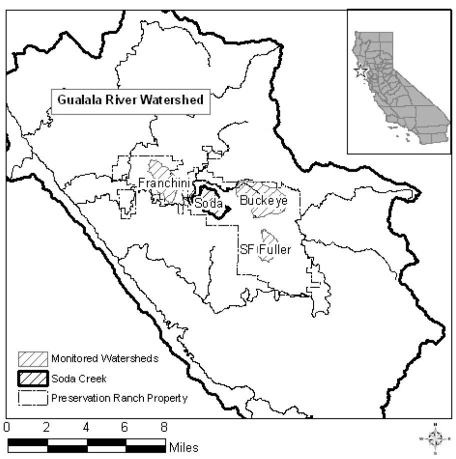

Figure 1—Location map.

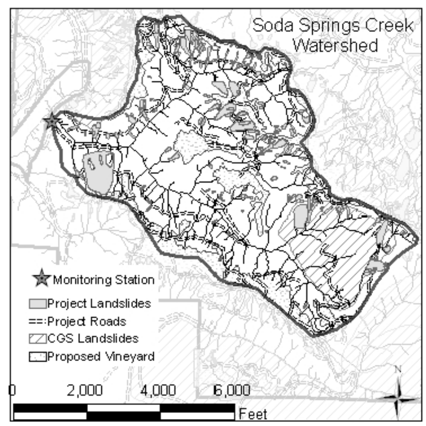

Figure 2—Study area attributes. “Project” and “CGS” refer to source for landslide data.

Methods

Prior sediment yield estimates were developed using SSA techniques for drainage areas of about 50 mi^2 by the North Coast Regional Water Quality Control Board (NCRWQCB 2001) in the Gualala River Watershed Technical Support Document for Sediment (TSD) and by the California Geological Survey (CGS) for an area of 298 mi^2 (Fuller and Custis 2002). The TSD provided estimates of sediment delivery rates to streams from both natural and anthropogenic sources. The CGS study focused on estimating background (“natural”) erosion rates associated with accelerated soil creep rates to streams adjacent to large rock slides and earthflows. Techniques in this analysis incorporate aspects of the NCRWQCB and CGS methods to estimate sediment yield under existing conditions in four small watersheds (1.2 to 3.1 mi^2, *fig.1*).We substituted detailed local data on road erosion from field surveys, utilized a more detailed map of the stream network developed from field observations, and we added site specific data for landslides collected during field surveys of the project area.

Suspended sediment monitoring using the TTS system (Eads and Lewis 2002) was implemented in late 2005 with assistance from RiverMetrics LLC (Rand Eads, formerly of USDA Forest Service Redwood Sciences Lab).This program was conducted to validate sediment yield estimates based on sediment source assessment techniques and to establish baseline water quality and streamflow conditions. The initial analysis of TTS data for HY 2006 to 07 estimated annual suspended sediment yield (SSY) based on the regression relationships between turbidity-suspended sediment concentration (SSC) data pooled for each year (Eads 2007). A supplemental analysis of these data was based on regression relationships between turbidity and SSC on a storm-by-storm basis (Lewis 2009). In this study, we utilized a regression relationship between turbidity and SSC for pooled data from Soda Springs Creek for HY 2006 and 2007 to estimate SSY for HY 2008 through HY 2011 using turbidity and discharge data.

Sediment source assessment

Sediment sources were classified as background (natural) sources or anthropogenic (management-caused) sources. Background sources were comprised of three elements: rockslide and earthflow soil creep, bank erosion, and "natural" landslides (*table 1*). Anthropogenic sources were comprised of two elements: road-related erosion (including landslides) and erosion from skid-trails and log landings.

Table 1—*Summary of sediment source assessment data sources.*

Erosion Process	Principal Data Source
Rockslide and Earthflow Creep	• CGS landslide maps (Fuller and Custis 2002) • Project area landslide maps (Kleinfelder 2008) • Channel network maps for project area
Bank Erosion	Channel network maps for project area
Natural Landslides	TSD (NCRWQCB 2001)
Road-related Erosion (including landslides)	• Project area erosion rate estimates (PWA 2005) • Road network maps for project area • TSD road erosion rate estimates
Skid Trails & Landings	TSD

Rock slide and earthflow soil creep rates were estimated based on interpretation of literature data (Fuller and Custis 2002). They presented low- and high-range creep rate estimates. These soil creep rates to stream channels were differentiated based on the style of mass wasting and the activity class of the mass wasting feature (*table 2*). Additional data regarding the location and type of landslides (Kleinfelder 2008) supplemented existing data (Fuller and Custis 2002). Sediment delivery from soil creep was calculated as the product of two (representing two stream banks), average bank height of 3.3 ft (consistent with field observations), and stream length intersecting active and dormant mass wasting features (*table 2*) as determined from a GIS database.

Considering uncertainty of methods and assumptions, presenting erosion rate estimates as a range of values maintains an additional measure of caution with respect to interpretation and use of the estimates. In this study, we present sediment yield estimates as a range of values where possible. Low- and high-range rates were calculated for landslide soil creep per *table 2*.

Table 2—*Rock slide and earthflow soil creep rates (after Fuller and Custis 2002, adapted to include mass wasting classification of Kleinfelder 2007).*

Mass Wasting Process	Low-range creep rate (ft/yr)	High-range creep rate (ft/yr)
Historically active earthflow	0.427	0.984
Dormant earthflow	0.033	0.066
Historically active rock slides, slumps, flows and translational slides	0.082	0.164
Dormant rock slides, slumps and slump flows	0.016	0.033
Background creep (ordinary slope conditions)	0.005	--

Methods for estimating road erosion rates used by Pacific Watershed Associates (PWA) for the project area and for TSD field sites were similar. However, project area data are based on direct field observations of 37 miles of project area roads (PWA 2005a, 2005b), whereas the TSD estimates are based on a smaller sample of field plots supplemented by aerial photo interpretation. The mean historic road erosion rate estimated for the project area over the past 30 years was 85 t/mi/yr. The estimated sediment yield from existing roads in Soda Springs Creek is the product of historic erosion rate and road length (*fig. 2*).The TSD estimate is comprised of mass wasting (landslides), stream crossing failures, gullying and surface erosion, and is estimated to be 920 t/mi^2/yr. TSD-estimated sediment delivery from roads for Soda Springs Creek is a function of watershed area. Low-range rates of road-related erosion were those estimated from field surveys in the study area; high-range rates of road erosion were those estimated in the TSD.

Sediment yield measurement by TTS

Hydrologic data used to estimate sediment loads were collected through use of the TTS system developed at the Redwood Sciences Laboratory (RSL), a field office of the USDA Forest Service, Pacific Southwest Research Station (Eads and Lewis 2002). “TTS was designed to permit accurate determination of suspended sediment loads by establishing a relation between SSC and turbidity for each sampling period with significant sediment transport. It does so by collecting pumped suspended sediment samples when pre-selected turbidity conditions, or thresholds, are satisfied. During analysis the relations are applied to the nearly continuous turbidity data for the respective sampling periods to produce a continuous record of estimated SSC. The product of discharge and estimated SSC is then integrated to obtain accurate suspended sediment yields.”

Data collection began in mid-December 2005 at Soda Springs Creek. Full implementation of TTS with SSC sampling continued through May of 2007.The number of samples processed was 285 in HY 2006 and 161 in HY 2007.Continuous stage and turbidity are still being measured using the TTS program as of June 2011, however SSC sampling was discontinued after HY 2007.

Data processing and sediment load estimation procedures

Sediment loads for Soda Springs Creek have been estimated for HY 2006 to HY 2011 using TTS analysis procedures (Lewis and Eads 2009).Raw stage and turbidity data were compiled and adjusted using the TTS Adjuster software developed by the USDA Forest Service Redwood Sciences Laboratory[4]. Adjusted stage values were used to estimate instantaneous discharge, and adjusted turbidity was used as a surrogate for SSC. Discharge is multiplied by SSC to compute sediment yield for each data interval (10 minutes) and summed to estimate the sediment yield for any given period. For HY 2006 to HY 2010 turbidity was the only SSC surrogate used. During HY 2011 there were some periods with questionable turbidity data related to fouling of the turbidity sensor. For these periods, flow was used as a surrogate for SSC. Stage-discharge relationships (rating curves) for HY 2006 and 2007 are the same equations used by Lewis (2009).The rating curve for HY 2008 to HY 2011 represents the most up to date stage discharge relationship as of June 2011.

Annual sediment loads were calculated with R software according to TTS procedures (Lewis and Eads 2009). Sediment loads were estimated using four different regression relationships of SSC on turbidity: 1) simple linear regression: y = ax + b, 2) simple linear regression on the natural logarithms of both variables[5]: log (y) = a + b log (x), 3) power function: y = axb, 4) loess (non-parametric locally-weighted) regression (Cleveland and Devlin. 1988). Each of these models was fitted to three different data sets: HY 2006 only, HY 2007 only, and HY 2006-2007 pooled. The resulting 12 sediment load estimates for each year provide an indication of the uncertainty associated with model selection and interannual sampling variability.

Results

Sediment source assessment

Sediment yield estimates for Soda Springs Creek (sub-watershed of Buckeye Creek) from this analysis (Project) are compared with sediment yield estimates from CGS and the TSD (*table 3*). CGS estimates only the natural background rate associated with soil creep. Nevertheless, the CGS upper range estimate (3,019 t/mi^2/yr) is about twice the TSD and Project (upper range) estimates of 1,400 t/mi^2/yr and 1,688 t/mi^2/yr, respectively. The CGS low-range estimate (994 t/mi^2/yr) is 71 percent of the TSD estimate and 59 percent of the low range estimate for the Project (1,168 t/mi^2/yr).

Comparison between estimates from the TSD and the Project are more relevant given the comprehensive scope and spatial scale of erosion processes considered. The Project estimate is based on some of the same rate estimates used in the TSD. The TSD natural mass wasting rate (170 t/mi^2/yr) is added to rock slide/earthflow creep calculated for the Project. The high range road estimate and the skid trail/timber rate for the Project are from the TSD estimates for Buckeye Creek.

[4] http://www.fs.fed.us/psw/topics/water/tts/adjuster/AdjusterManual.html.
[5] In this analysis, all logarithms are natural logarithms (base e = 2.718282).The bias of retransformation, i.e., that introduced when transforming log(*y*) to *y*, was corrected using the minimum variance unbiased estimator (Cohn et al 1989).

The Project low-range and high-range estimates are 83 and 121 percent of the Buckeye Creek estimates, respectively. The range of natural background sediment yield estimated for the Project is greater than that estimated by the TSD, 454 to 648 t/mi^2/yr versus 360 t/mi^2/yr. The range of natural background sediment yield for the Project (Soda Springs Creek) is 126 to 180 percent of that estimated by the TSD for Buckeye Creek.

Table 3—*Summary of sediment yield estimates (t/mi^2/yr) using sediment source assessment methods.*

Sediment Source	CGS (Gualala River, 298 mi^2)	TSD (Buckeye Creek, 40.3 mi^2)	Soda Springs Creek (1.53 mi^2)
Natural Mass Wasting	975 – 2,998	170	343 - 537
Stream Bank Erosion	19 - 21	190	111
Road-Related Erosion	--	920	594 - 920
Skid-Trail/Timber Harvest	--	120	120
Total	994 – 3,019	1,400	1,168 – 1,688

Measured sediment yield

Turbidity and SSC data were closely correlated and least-squares fits to the data (e.g., *fig. 3*) were strikingly similar in HY 2006 and 2007.The coefficient of determination (r2) for all models and all data sets is relatively high, ranging from 0.88 to 0.96.For models fitted to the pooled data, r2 ranged from 0.90 to 0.92.

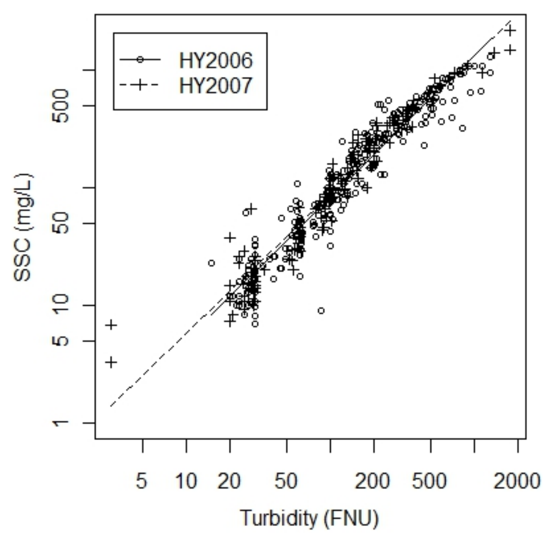

Figure 3—Regression on logs of turbidity and SSC

While an unknown error is introduced in using HY 2006-2007 data to estimate sediment yields for HY 2008 to 2011, the likely magnitude of that error appears to be small. The HY 2006 relationship produced mean annual sediment yield ranging from 186 to 218 t/mi^2/yr, while the HY 2007 relationship produced only slightly higher mean annual sediment yields ranging from 192 to 219 t/mi^2/yr. The loess model (r^2 = 0.92) produced the lowest estimates and the power model (r^2 = 0.91) the highest. The model based on the relationship for pooled data gave mean annual sediment yield ranging from 194 to 216 t/mi^2/yr.

Sediment yield (fig. 4) measured in HY 2006 is by far the greatest during the period of record, ranging from about 620 to 710 t/mi^2/yr. The lowest sediment yield, about 30 t/mi^2/yr, was measured in HY 2009.

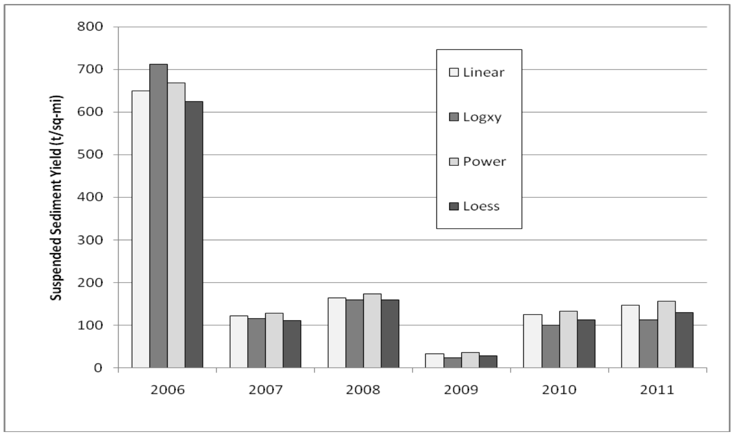

Figure 4—Sediment yield estimates based on HY 2006-07 pooled data regressions.

Discussion

SSA yield estimates substantially exceed measured SSY for Soda Springs Creek. In HY 2006, measured sediment yield (about 620 to 710 t/mi^2/yr) represents about one-half that estimated by the TSD[6]. The HY 2006 measured sediment yield is 37 to 61 percent of estimated yield from the Project SSA (*table 3*). In subsequent years, measured yield is about ten percent of yields predicted by SSA. The difference between SSA-predicted yield and measured SSY is considerably less than the magnitude of uncertainty in measured SSY attributable to sampling and modeling error hypothesized above.

Part of the discrepancy between predicted and observed sediment yield is attributable to unmeasured bedload sediment transport. Bedload (typically sand and gravel) is transported infrequently and over short distances relative to suspended sediment load. The TTS method does not account for bedload sediment. The magnitude of bedload sediment yield can be estimated using regional ratios of bedload to suspended load. Bedload and SSY have been estimated for North Fork Caspar Creek (1.8 mi^2), a watershed with geologic and hydrologic characteristics similar to Soda Springs Creek. Estimates of the ratio of bedload to suspended load range from 15:85 (Napolitano 1996) to 30:70 (Cafferata and Spittler 1998). Based on these ratios, total sediment yield would be about 18 to 43 percent greater than SSY. Total sediment yield for HY 2006 would range from about 730 to 1,020 t/mi^2/yr, a rate that approaches the low-range prediction for Soda Springs Creek (*table 3*). Adjusted for unmeasured bedload transport, mean annual sediment yield for HY 2006 to 2011 ranges from 229 to 308 t/mi^2/yr. Unmeasured bedload does not appear

[6]A portion of HY 2006 (October, November and early December 2005) was unmeasured as monitoring stations were being installed, hence the sediment yield measured for HY 2006 is an underestimate. However, the unmeasured flows represent less than ten percent of flow recorded in that year based on comparison with other regional data.

to be great enough to account for the discrepancy between measured yields and those estimated by sediment source methods.

SSA methods rely on numerous assumptions to develop quantitative estimates of erosion and sediment delivery rates. Field measurements of landslide scarps and gullies can be made with reasonable accuracy, however, the timing of erosion and the proportion of soil delivered to a stream from a source is difficult to determine. Soil creep rates estimated from literature values may represent average conditions, but variability related to geologic conditions and climate is complex. Eroded sediment may be temporarily deposited on hillslopes, in stream channels, and on alluvial fans, awaiting geomorphic events capable of remobilizing it. Erosion processes are episodic, with periods of quiescence punctuated by extreme events associated with large storms and floods in the California Coast Range. Hence it is not surprising that estimates of sediment yield from source assessment methods could diverge from measured sediment yields.

Conclusion

Sediment source assessment methods that estimate mean annual sediment yield do not always provide accurate estimates of actual sediment yields, nor do they account for inter-annual variability related to climate conditions. Measurement of sediment yield using TTS methods allows for validation of sediment source assessments and provides an alternative means of evaluating watershed sediment yield. Field studies involving more direct measurement of erosion and sediment transport processes appear to be required to validate sediment source assessments.

References

Cafferata, P.; Spittler, T. 1998. **Logging impacts of the 1970's vs. the 1990's in the Caspar Creek watershed.** In: Ziemer, R., technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story. Gen. Tech. Rep. PSW-GTR-168. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 103-116.

Cleveland, W.S.; Devlin, S.J. 1988. **Locally-weighted regression: an approach to regression analysis by local fitting.** Journal of the American Statistical Association 83: 596-610.

Eads, R. 2007. **Preservation Ranch suspended sediment load analysis for Buckeye, Franchini, Soda, and South Fork Fuller Creek-Hydrologic years 2006-2007.** RiverMetrics LLC. Prepared for O'Connor Environmental, Inc., Healdsburg, CA. 41 p.

Eads, R.; Lewis, J. 2002. **Continuous turbidity monitoring in streams of northwestern California.** In: Glysson, G.; Gray, J., editors. Proceedings of the federal interagency workshop on turbidity and other sediment surrogates. Reno, NV: U.S. Geological Survey. 3 p.

Fuller, M.;Custis, K. 2002. **Geology and geomorphology for Gualala River watershed assessment.** Department of Conservation, California Geological Survey. CD2002-08.

Klamt, R.R.; LeDoux-Bloom, C.; et al. 2002. **Gualala River watershed assessment report.** Sacramento, CA: North Coast Watershed Assessment Program. California Resources Agency and California Environmental Protection Agency. 367 p.

Kleinfelder, Inc. 2008. **Landslide hazard evaluation, Preservation Ranch, northwest Sonoma County, California.** Report prepared for Preservation Ranch.18 p. .

Lewis, J. 2009. **Evaluation of baseline data for Preservation Ranch conversion project: storm suspended sediment, peak flow, flow volume, and turbidity-hydrologic years 2006-2007.** Prepared for O'Connor Environmental Inc. Healdsburg, CA. 61 p.

Lewis, J.L.; Eads, R.D. 2009. I**mplementation guide for turbidity threshold sampling: principles, procedures, and analysis.** Gen. Tech. Rep. PSW-GTR-212. Arcata, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 87 p.

Napolitano, M.B. 1996. **Sediment transport and storage in North Fork Caspar Creek, Mendocino County, California: water years 1980-1988.** Arcata, CA: Humboldt State University. M.S. thesis. 148 p.

NCRWQCB. 2001. **Gualala River watershed technical support document for sediment. North Coast Regional Water Quality Contrrol Board, Santa Rosa, CA.** 138 p.

O'Connor Environmental, Inc. 2008. P**reservation ranch sediment source assessment and evaluation of project effects.** Prepared in association with Kleinfelder. 71 p.

Pacific Watershed Associates (PWA). 2005a. **Draft summary report, phase 1 mainline road inventory and upgrading plan, Preservation Ranch, Gualala River Watershed.** Prepared for Winzler & Kelly Consulting Engineers, Eureka, CA. 56 p.

Pacific Watershed Associates (PWA). 2005b. **Phase 2 road inventory and upgrading plan, Presevation Ranch, Gualala River Watershed.** Prepared for Winzler & Kelly Consulting Engineers, Eureka, CA. 106 p.

Parrett, C.; Hunrichs, R. 2006. **Storms and flooding in California in December 2005 and January 2006--a preliminary assessment.** US Geological Survey. Open File Report 2006-1182: 8.