Timber Harvest and Turbidity in North Coastal California Watersheds

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Abstract

Turbidity regimes vary dramatically among small streams in north coastal California. In an analysis of turbidity data from 27 small streams in the region, turbidity at the 10-percent exceedence level ranged from 3 to 116 formazin nephelometric units (FNU) for the 2005 wet season, translating to 1.7 to 65 days above an oft-cited biological threshold of 25 FNU. Watersheds draining to the streams spanned disturbance categories from zero (pristine redwood forest) to intense commercial timber harvest. Grouping the sites by average annual timber harvest rate showed that the zero harvest (background) group averaged 13 FNU at the 10-percent exceedence level, while the low harvest group averaged 20 FNU and the high harvest group averaged 61 FNU, 58 percent and 369 percent, respectively—well above the "20 percent above background" regulatory limit for northern California streams.

Regression analyses of turbidity on watershed natural physiographic characteristics and land use histories (timber harvest and roads) showed the rate of recent timber harvest (average annual percent of watershed area) explained the greatest amount of variability in 10-percent turbidity exceedence. Drainage area was also significant but was secondary to harvest rate. None of the other watershed variables was found to improve the regression models. Despite much improved best management practices, contemporary timber harvest can trigger serious cumulative watershed effects when too much of a watershed is harvested over too short a time period.

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Introduction

It is widely acknowledged that historically intense timber harvest increased erosion and sediment delivery rates to extreme levels in the 1950s through the 1970s across the north coast of California (see Nolan and Janda 1995). Residual water quality effects from historical harvest certainly continue today to some degree. What is less certain, and more relevant to present-day management, is the extent to which contemporary timber harvest contributes to erosion, sediment delivery, and turbidity leading to cumulative watershed effects that can imperil the health and sustainability of aquatic ecosystems.

The term "chronic turbidity" has been used to describe the long-duration turbidity regime that includes levels below those that occur during peak stormflows, yet are high enough to cause biological impacts. Evaluating the role of contemporary timber harvest in chronic turbidity was accomplished by assembling stream turbidity datasets from regional watersheds and relating turbidity regimes to both natural and anthropogenic watershed attributes that likely affect turbidity. Recent technological advances allow automated collection of virtually continuous turbidity data, a relatively new means of stream turbidity monitoring that yields datasets of unprecedented detail. Using continuous turbidity data from 27 stations, turbidity at the 10-percent exceedence level was used as a metric for chronic turbidity. This paper presents a portion of a larger analysis by Klein et al. (2008) that evaluated causes of chronic turbidity and effects on anadromous salmonids.

The concept of determining "threshold" rates of timber harvest (i.e., rates above which environmental impacts become excessive) is not new. Reeves et al. (1993) found harvest rate to be inversely associated with salmonid assemblage diversity. The California Department of Forestry and Fire Protection, in drafting harvest guidelines for the California Board of Forestry, suggests timber harvest exceeding 20 percent of a watershed within a 10-year period (equating to an average annual harvest rate of 2 percent) could result in consideration of a watershed as "sensitive" (Munn and Cafferata 1992). Tuttle (1992) recommends that harvesting 15 percent of a watershed's area with even-aged management (clearcut) within a decade (equating to an annual harvest rate of 1.5 percent) be used as a threshold for triggering examination of impacts on beneficial uses of water, including fish.

Those working on developing timber harvest rate guidelines in California generally converge on an annual average timber harvest rate of about 1.5 to 2 percent of watershed area as an upper limit or a trigger for more detailed analysis, but efforts to implement harvest rate limits have thus far failed with one exception. In 2006, the North Coast Regional Water Quality Control Board ordered that harvest rates in Elk River and Freshwater Creek (two Humboldt County streams included in this analysis) be limited to approximately 2 pct/yr to minimize harvest-related landslide sediment discharges and reduce nuisance flooding of downstream landowners caused by channel aggradation (North Coast Regional Water Quality Control Board 2006).

Study Area

The 27 north coastal California watersheds for which turbidity data were assembled range in drainage area from 2.9 to 72.8 km^2, with several smaller watersheds nested within larger ones. All are located in coastal California mountain ranges from about 240 to 500 km north of San Francisco. Because these are small coastal watersheds, snow accumulation and melt are seldom hydrologically significant. Turbidity levels in the region are largely a function of suspended sediment concentrations, and the two are typically well-correlated (Lewis 2002). The largest proportion of stream suspended loads consists of inorganic particles generated from erosion of mineral soils and rock via surface erosion from bared areas, gullies, and mass erosion processes.

The region is subject to high rates of tectonic uplift and strong earthquakes. Slopes are typically steep and soils highly erodable. Rainfall occurs almost exclusively in the winter months, often as multiday intense rainfall events that produce large floods. The combination of these factors results in some of the highest sediment loads in the United States (although there is considerable variability within the region), and while much can be attributed to natural processes, human disturbance can greatly accelerate erosion and sediment delivery to streams.

The study watersheds included several that are virtually pristine redwood forests and several harvested 40+ years ago residing in Redwood National and State Parks. Others are located on private timberlands and subject to varying levels of past and ongoing timber harvest along with minor influences from ranching and residential development. Two of the streams (North and South Forks Caspar Creek) are located within an experimental forest that is the site of long-term watershed research (Lisle 2005).

Methods

To prepare for the analysis, continuous (10- or 15-min sampling interval) turbidity data sets were assembled from a variety of sources, including Federal agencies, a nonprofit group, a private timber company, and individuals (see Klein et al., 2008, for a detailed listing of data contributors). In addition to turbidity, datasets also included continuous stream stage and often discharge data.

Automated turbidity data were collected by deploying sensors in the water column using an articulating boom secured above the stream (see Eads and Lewis, 2002, for a description). An onshore data logger controls sensor operation and records stage and turbidity data. It is rare for an automated turbidity dataset to be free from spurious observations upon retrieval from the field. Raw data must be reviewed and corrected as needed prior to being considered representative of field conditions and thus ready for analysis. Most data contributors provided corrected turbidity data, but some data were provided in raw form and needed corrections.

To make corrections, data were imported to a common spreadsheet and plotted along with stage and (or) discharge data. Such plots are essential for revealing suspect data, which usually consist of short duration spikes reflecting a leaf or some other object obscuring the sensor optics, or gradually ascending values that reflect algal growth on the sensor's optics. Corrections consisted of reducing suspect values to match valid observations bounding the suspect data. Corrected observations typically composed very small percentages of the full datasets used.

Another important issue in comparative turbidity studies is compatibility (or lack thereof) of data collected using different sensor types or makes. In laboratory testing, Lewis et al. (2007) found that different sensors returned sometimes very different turbidity values when immersed in the same sediment type and concentration. The greatest differences occurred at high turbidities. The present study included data from two sensor types commonly used for stream studies in the region: the OBS-3 sensor (formerly made by D&A Instruments Company, presently made by Campbell Scientific, Inc.) and the DTS-12 sensor (made by Forest Technology Systems, Inc.). A set of equations was developed using the results of Lewis et al. (2007) to convert the data from the OBS-3 to equivalent values for the DTS-12 before conducting turbidity exceedence analyses, as detailed in Klein et al. (2008). Data for the 2005 winter runoff season (WY2005) were assembled and prepared for analysis.

Before performing exceedence analyses, datasets were truncated to only include data from December 2004 through May 2005, the period each season that typically encompasses almost all turbidity events. Although this period excluded several small, early-season storms, several of the datasets assembled had irreparable or no data prior to December. The 10-percent exceedence probability (the turbidity level exceeded 10 percent of the time being considered, or "10%TU") was derived from the continuous data to represent chronic turbidity.

Geographical information system data were obtained for the study watersheds to characterize both the naturally and human-affected propensity for watershed erosion and stream turbidity. Data categories included watershed physiographical characteristics (hypsometry, slope steepness, stream density), slope stability modeling results, history of timber harvest and associated activities (yarding, road building), attributes of the road network, and rainfall intensities.

Different types of timber harvest impose different disturbance levels per unit area of harvest, with clearcut harvesting and tractor yarding (still widely used) creating the greatest disturbance. Consequently, harvest areas were weighted by silvicultural method according to state guidelines (North Coast Regional Water Quality Control Board 2006) to account for varying levels of ground disturbance and potential water quality impacts. Weighting of the silvicultural methods reduced the actual areas of lower disturbance types, and resultant harvest rate variables were expressed as "clearcut equivalent area." Harvesting, yarding and road building data going back 15 years (1990–2004) before the turbidity data set (WY2005) were assembled from timber harvest plan records kept by the California Department of Forestry and Fire Protection. This period was also broken into three 5-yr periods (1990–1994, 1995–1999, and 2000–2004) to explore the relative importance of harvest age. Clearcut equivalent harvest rate was expressed as the annual average percent of watershed area for individual time periods used.

Multiple regression analyses were performed to determine which watershed variables best explained differences in chronic turbidity among the watersheds. Regressions were performed on two groups: all 27 streams and just the subset of the northernmost 19 streams loosely clustered in Humboldt County, CA. Regressions began by using only the highest correlate with the Y-variable (10%TU) from each watershed variable category, and additional variables were subsequently added if they significantly improved the model (J. Lewis, 2007, U.S. Forest Service, Redwood Sciences Laboratory, personal commun.). The primary diagnostic for evaluating model improvement was Akaike's Information Criterion (AIC) (Sakamoto et al. 1986). The best model was considered to be the one that minimized the AIC.

Results

Rainfall for WY2005 was near normal at about 90 percent of average in the northern portion of the study area, and slightly above normal in the southern portion. Annual average harvest rate (expressed as clearcut equivalent area averaged over the 15 years prior to the turbidity data record used) ranged from 0 to 3.7 percent. Turbidities at the 10-percent exceedence probability ranged from 3 to 116 formazin nephelometric units (FNU) among the 27 streams. Perhaps more tangible for many readers, the cumulative time above 25 FNU spanned a factor of 100, ranging from 15 to 1,566 hrs. Water in the most turbid streams rarely (and only briefly) fell below 25 FNU (threshold for biological effects) the entire wet season. In contrast, some streams were exceptionally clear, with five located in Federally protected areas only exceeding 100 FNU for 0–2 hrs total in WY2005, and only exceeding 25 FNU for 34–71 hrs total. Table 1 summarizes turbidity results for the study streams grouped by annual average harvest rate.

Table 1. Means (and ranges) of 10-percent exceedence probability turbidites ("10%TU") and cumulative hours above threshold (25 FNU) for three harvest rate groups.

1990–2004 Harvest rate group	**10% TU (range)**	**Hours >25 FNU**
Zero harvest (0%/yr)	13 (3–22)	198
Lower (0.1–1.5%/yr)	20 (4–37)	448
Higher (>1.5%/yr)	61 (26–116)	1,116

Of the variables used for explaining turbidity differences among the watersheds, timber harvest rate averaged over the 15 preceding years was the strongest correlate (r = 0.71) with chronic turbidity among the full set of 27 streams. Of the other harvest rate periods investigated (0–5, 0–10, 5–10, and 10–15 yrs prior to the turbidity record), the period 10–15 yrs prior was the next highest correlate (r = 0.69). Drainage area was the highest correlate among the natural variables (r = 0.62). Each of these variables was directly related to turbidity; i.e., when harvest rate and (or) drainage area goes up, so does turbidity.

The best fit from multiple regression analyses using both the full set of streams (n = 27) and the Humboldt County subset (n = 19) included just two explanatory variables: clearcut equivalent area for the period 10–15 yrs before the WY2005 turbidity record and drainage area. The full set model resulted in an AIC of 236 and an adjusted multiple r-squared of 0.63. Other models using just harvest rate (including annual harvest rate averaged 0–15 yrs prior to the turbidity record) also performed well. Regressions using the Humboldt County stream subset (n = 19) had a superior fit over that for the full set with an AIC of 158 and an adjusted multiple r-squared of 0.82 (J. Lewis, 2007, U.S. Forest Service, Redwood Sciences Laboratory, personal commun.).

Conclusions

The rate of timber harvest, expressed as annual average clearcut equivalent area for the 15 years preceding the turbidity data record, explained much of the large differences in chronic turbidity among the study watersheds, with drainage area playing a subordinate but still significant role. These findings demonstrate the importance of recent timber harvest and were consistent with the earlier results of Klein (2003) in a similar study.

Basin geomorphic characteristics reflect basin-shaping processes and susceptibility to erosion-accelerating disturbances. To account for this, several variables were derived for the study watersheds to serve as surrogates for natural erosion susceptibility. However, their contribution in explaining turbidity variations was insufficient to be included in the best fit regression models. Certainly, natural factors that determine the inherent erosional susceptibility of hillslopes exert strong control on stream water quality, but with the exception of drainage area, they were overshadowed by human disturbance in this study. By narrowing the geographical range of streams to just the Humboldt County subset, natural variability was reduced and regression results were improved. Further research may ultimately result in more robust variables for characterizing natural erosion susceptibility.

Forest roads are widely recognized as culprits in elevated erosion and sediment delivery in forested steeplands. Reid (1998) modeled effects of fine sediment production from roads using cumulative stream turbidity duration curves. Her results suggested that road-related erosion would cause large increases in chronic turbidity, elevating the duration of turbidities above 100 NTU by a factor of 73.

Contrary to expectations and conventional wisdom, road variables used here had little added statistical value beyond harvest rate and drainage area in explaining turbidity variations, possibly resulting from incomplete and (or) inaccurate road data. For example, road lengths are probably under-represented in "off-the-shelf" datasets. Perhaps more accurate road data would have elevated the importance of road variables in explaining turbidity. But roads were indirectly accounted for in that they are closely linked to harvest rate: the density of the road network and the intensity of road use rise with increasing harvest rate.

Comparison of turbidity exceedences among watershed harvest class groupings (zero-, low-, and high-harvest rates) showed the low-harvest group to be 58 percent and the high-harvest group to be 369 percent, respectively, above the regulatory limit for northern California streams (20 percent above background). All but two actively harvested watersheds would have been out of compliance with this standard in WY2005. It is important to note that most zero-harvest watersheds included here were not pristine; they had been harvested prior to the period from which harvest data were considered (1990–2004). Although legacy erosion features were no doubt still active in these watersheds, turbidities were far lower than in actively-harvested watersheds.

Although the rate of timber harvest has been acknowledged among California scientists, regulatory agencies, and legislators as a factor in declining water quality and aquatic habitat for some time, little has been accomplished toward enacting regulatory controls. Instead, the regulatory community has largely relied on site-specific best management practices (BMPs) in attempting to prevent degradation of water quality. While BMPs have helped reduce site-specific erosion and resultant turbidity effects from timber harvest, they are neither perfectly conceived nor perfectly implemented, and severe degradation of water quality can still arise in watersheds where too much of the land base is harvested over too short a time period.

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References

Eads, R., and J. Lewis. 2003. Continuous turbidity monitoring in streams of northwestern California. In J.R. Gray and G.D. Glysson, eds., Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, Reno, NV, 30 April–2 May 2002, unnumbered pages. U.S. Geological Survey, Circular 1250.

Janda, R.J., K.M. Nolan, D.R. Harden, and S.M. Colman. 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California. U.S. Geological Survey, Open File Report 75-568.

Klein, R.D. 2003. Duration of turbidity and suspended sediment transport in salmonid-bearing streams, north coastal California. Report to U.S. Environmental Protection Agency, San Francisco, CA.

Klein, R.D., W.J. Trush, and M. Buffleben. 2008. Watershed condition, turbidity, and implications for anadromous salmonids in north coastal California streams. Report to North Coast Regional Water Quality Control Board, Santa Rosa, CA.

Lewis, J. 2002. Estimation of suspended sediment flux in streams using continuous turbidity and flow data coupled with laboratory concentrations. In J.R. Gray and G.D. Glysson, eds., Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, Reno, NV, 30 April–2 May 2002, unnumbered pages. U.S. Geological Survey, Circular 1250.

Lewis, J., R. Eads, and R.D. Klein. 2007. Comparisons of turbidity data collected with different instruments. Report to California Department of Forestry and Fire Protection and the

North Coast Regional Water Quality Control Board, Santa Rosa, CA.

Lisle, T.E. 2005. Caspar Creek Experimental Watersheds: Cumulative effects of forest practices on downstream resources. U.S. Forest Service, Pacific Southwest Research Station, Science Perspectives–September 2005 (PSW-SP-005).

Munn, J., and P. Cafferata. 1992. Draft Sensitive Watershed Criteria. California Department of Forestry and Fire Protection, Sacramento, CA.

Nolan, K.M., and R.J. Janda. 1995. Impacts of logging on stream-sediment discharge in the Redwood Creek basin, northwestern California. In K.M. Nolan, H.M. Kelsey, and D.C. Marron, eds., Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California, pp. L1–L8. U.S. Geological Survey, Professional Paper 1454.

North Coast Regional Water Quality Control Board. 2006. Watershed-wide waste discharge requirements for timber harvesting plan activities, Salmon Creek Corporation, and the Pacific Lumber Corporation in the Elk River watershed. North Coast Regional Water Quality Control Board, Order No. R1-2006-0039.

Reeves, G.H., F. Everest, and J. Sedell. 1993. Diversity of juvenile anadromous salmonid assemblages in Coastal Oregon basins with different levels of timber harvest. Transactions American Fisheries Society 122(3):309–317.

Reid, L.M. 1998. Forest roads, chronic turbidity, and salmon. In Abstracts of the American Geophysical Union 1998 Fall Meeting, San Francisco, CA, 6–10 December 1998, Abstract no. HIIF-05. American Geophysical Union.

Sakamoto, Y., M. Ishiguro, and G. Kitagawa. 1986. Akaike Information Criterion Statistics. D. Reidel Publishing Company, Dordrecht, Netherlands.

Tuttle, A. 1992. Sensitive Watershed Rule Package. California State Board of Forestry, staff paper.