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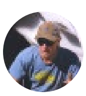
ARTICLE *in* GEOMORPHOLOGY · FEBRUARY 2012

Impact Factor: 2.58 · DOI: 10.1016/j.geomorph.2011.10.011

3 AUTHORS:



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Geomorphology xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Logging and turbidity in the coastal watersheds of northern California

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ARTICLE INFO

Article history:
Received 21 April 2011
Received in revised form 7 October 2011
Accepted 8 October 2011
Available online xxxx

Keywords:
Turbidity
Timber harvest
Cumulative watershed effects
Best management practices

ABSTRACT

Continuous turbidity data for the 2004–2005 winter runoff seasons were used to assess water quality characteristics in 28 coastal watersheds in northern California. Turbidity probes collected data during the winter period, typically spanning the months of October–May. Stream biota, such as salmonids, suffer not only from turbidity extremes but also from chronic turbidity. We used turbidity at the 10% exceedence level to index chronic turbidity in the 28 streams. Watersheds draining to the streams spanned disturbance categories from pristine redwood forest to intensive commercial timber harvest. Grouping the sites by timber harvest history showed that the pristine (unharvested, or 'background') group mean was 8 FNU (formazin nephelometric units) at the 10% exceedence level in water year 2005 (WY2005), while the legacy (older) harvest, low, and high harvest rate group means were 16, 32, and 61 FNU, respectively. Regression analyses of turbidity on watershed natural physiographic characteristics and land use histories (logging and roads) showed the rate of recent logging (mean annual percent of watershed area) explained the greatest amount of variability in turbidity at the 10% exceedence level. 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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1. Introduction

Degradation of water quality – especially turbidity and suspended sediment – has long been recognized as one of the most important risks from timber harvest and road building. Lieberman and Hoover (1948) measured a 22-fold increase in mean turbidity and a 42-fold increase in the maximum turbidity because of the style of logging employed in the mid-20th century. Nolan and Janda (1995) computed suspended sediment discharges at stream gaging stations in Redwood Creek, finding that recently logged watersheds yielded 10 times more suspended sediment than unharvested terrain. Gomi et al. (2005) compiled data from numerous studies of logging effects in the western US, with post-logging suspended sediment yield increases ranging from 0 to 1000% and post-logging recovery times ranging from zero to over four years. Keppeler et al. (2003, p. 5) reported that "sediment yields do not appear to recover as quickly [as streamflows] and persist at double the pretreatment levels 12 years after harvest" for tributaries in North Fork Caspar Creek, California.

Elevated turbidity and suspended sediment concentrations and durations can have negative short- and long-term effects on aquatic biota. Salmonids in particular may be adversely affected at several life stages in freshwater (Newcombe and MacDonald, 1991; Newcombe and Jensen, 1996; Henley et al., 2000; Newcombe, 2003), although White and Harvey (2007) found that in some cases, adaptive feeding strategies used by trout may overcome difficulties in finding food in turbid conditions. Klein et al. (2008, Part B) detailed the linkages between harvest rates, elevated chronic turbidity, reduced growth of juvenile salmonids, and impaired spawning escapement. Furthermore, Reeves et al. (1993) found that harvest rate was inversely associated with juvenile salmonid diversity.

Most research has implicated logging roads as the foremost harvest-related feature in elevated erosion and sedimentation. Roads, landings, and skid trails can be a source of landslides (Keppeler et al., 2003) and surface erosion (e.g., Reid and Dunne, 1984; Johnson, 1988). Within-unit erosion and sediment delivery from mass movement and gullying also contribute to elevated post-logging sediment discharge (e.g., Brardinoni et al., 2003; Reid et al., 2010).

Timber harvesting and road building standards have certainly evolved since Lieberman and Hoover (1948) conducted their study. Forest practice rules in California (following passage of the Z'berg-Nejedly Forest Practice Act of 1973) devote much language to restricting practices that were most damaging to streams and hillslopes. Numerous rule changes and additions have been incorporated since the 1970s. The rules are, in effect, best management practices (or BMPs), and are generally considered to perform reasonably

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0169-555X/$ – see front matter Published by Elsevier B.V.
doi:10.1016/j.geomorph.2011.10.011

well if implemented properly and in a timely manner. However, BMPs, even when aggressively applied, cannot prevent all erosion from harvested slopes and forest roads (Keppeler et al., 2003; Reid et al., 2010), and the cumulative effects from multiple harvest areas may be additive (Lewis et al., 2001) or synergistic where one erosion feature triggers another (e.g., a debris flow plugs a culvert, which then diverts stormflow down a logging road, triggering gully formation and landsliding) or a biological threshold is crossed. Consequently, although BMPs may reduce erosion and sediment delivery for a given harvest area relative to unregulated harvesting, if too large a proportion of a watershed is subject to harvest-related disturbances in a compressed time frame, water quality can be seriously degraded and stream biota harmed (Henley et al., 2000; Klein et al., 2008).

The use of turbidity to assess the water quality impacts of forestry operations has increased in California and is used at various scales (Harris et al., 2007). Long-term turbidity monitoring programs, some limited to grab sampling, have been used to detect recovery trends in Washington (Reiter et al., 2009). Since Lewis (1996) demonstrated the effectiveness of using turbidity as a surrogate for suspended sediment concentration in load estimation, many northern California stream gaging stations have been equipped with automated turbidity sensors coupled with pumping samplers. This technological shift has improved suspended load estimation over competing methods that rely on sediment rating curves and stream discharge. This paper utilizes the data being collected by automated turbidity sensors in forested watersheds along the northern California coast to identify watershed characteristics and land use histories that are the principal causes of elevated turbidity regimes.

2. Study area

Our study area spans three coastal counties in northern California (Del Norte, Humboldt, and Mendocino counties, Fig. 1). All are located in the Coast Range Mountains from about 240 to 500 km north of San Francisco. The region is subject to high rates of tectonic uplift and strong earthquakes. Slopes typically are steep and soils highly erodible. 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 U.S. (Paulson et al., 1993), although within-region variability is considerable. While much can be attributed to natural processes, human disturbance can greatly accelerate erosion and sediment delivery to streams.

The 28 watersheds for which turbidity data were assembled range in drainage area from 2.9 to 72.8 km^2 (Table 1), with several smaller watersheds nested within larger ones. 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 portion of stream-suspended loads consists of inorganic particles generated from erosion of mineral soils and rock via surface erosion from bared areas, gully, and mass erosion processes. Adequate continuous turbidity data were available for up to 28 sites, as listed in Table 1.

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 or state-owned 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 Fork Caspar Creek) are located within an experimental forest that is the site of long-term watershed research (Henry, 1998).

3. Methods

To prepare for the analysis, continuous (10- or 15-minute sampling interval) turbidity data sets were assembled from various 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, data sets also included continuous stream stage and often discharge data. Our data analysis period spanned three water years (WY2003-2005), but not all of the 28 sites had adequate data for each year, as indicated in Table 1. Because WY2005 had the greatest number of sites with complete data, that year was chosen for more detailed analyses.

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. Only rarely are automated turbidity data sets 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 sensor optics or gradually ascending values that reflect algal growth on sensor optics. Corrections consisted of reducing suspect values to match valid observations bounding the suspect data. Corrected observations typically composed very small percentages (mean = 7%) of the full data sets used.

Another important issue in comparative turbidity studies is compatibility (or lack thereof) of data collected using different sensor types or makes (Davies-Colley and Smith, 2001). 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.). Equations were developed for application to specific watersheds using the results of Lewis et al. (2007), and OBS-3 data were converted to equivalent values for the DTS-12 before conducting turbidity exceedence analyses, as detailed in Klein et al. (2008). Data for the 2003, 2004, and 2005 winter runoff seasons (WY2003, 2004, and 2005) were assembled and prepared for analysis.

Before performing exceedence analyses, data sets were truncated to include data from only December–May, the rainy season that typically encompasses almost all turbidity events. Although this period excluded several small, early season storms, several of the assembled data sets had irreparable or no data prior to December. As with flow duration analyses, we sorted the turbidity data from largest to smallest and computed the percent of time each value was equaled or exceeded (i.e., exceedence probability). The 10% exceedence probability (that turbidity level exceeded 10% of the time being considered, or 10%TU) was derived from the continuous data to represent chronic turbidity. Turbidity at the 10% exceedence level captures stormflow turbidities that occur between storm peaks and winter baseflows, providing a single value to index chronic exposure for salmonids.

Geographical information system (GIS) and other data were obtained for the study watersheds to characterize both the natural and human-affected propensity for watershed erosion and stream turbidity. The variables considered for analysis are listed in Table 2. Data categories included natural watershed physiographical characteristics (hypsometry, slope steepness, stream density, slope stability modeling results, and rainfall intensities), historical timber harvest and associated activities (yarding, road building) from California timber harvest plan ('THP') records, and attributes of the road network. U.S. Geological Survey 10 m DEM data were used to compute

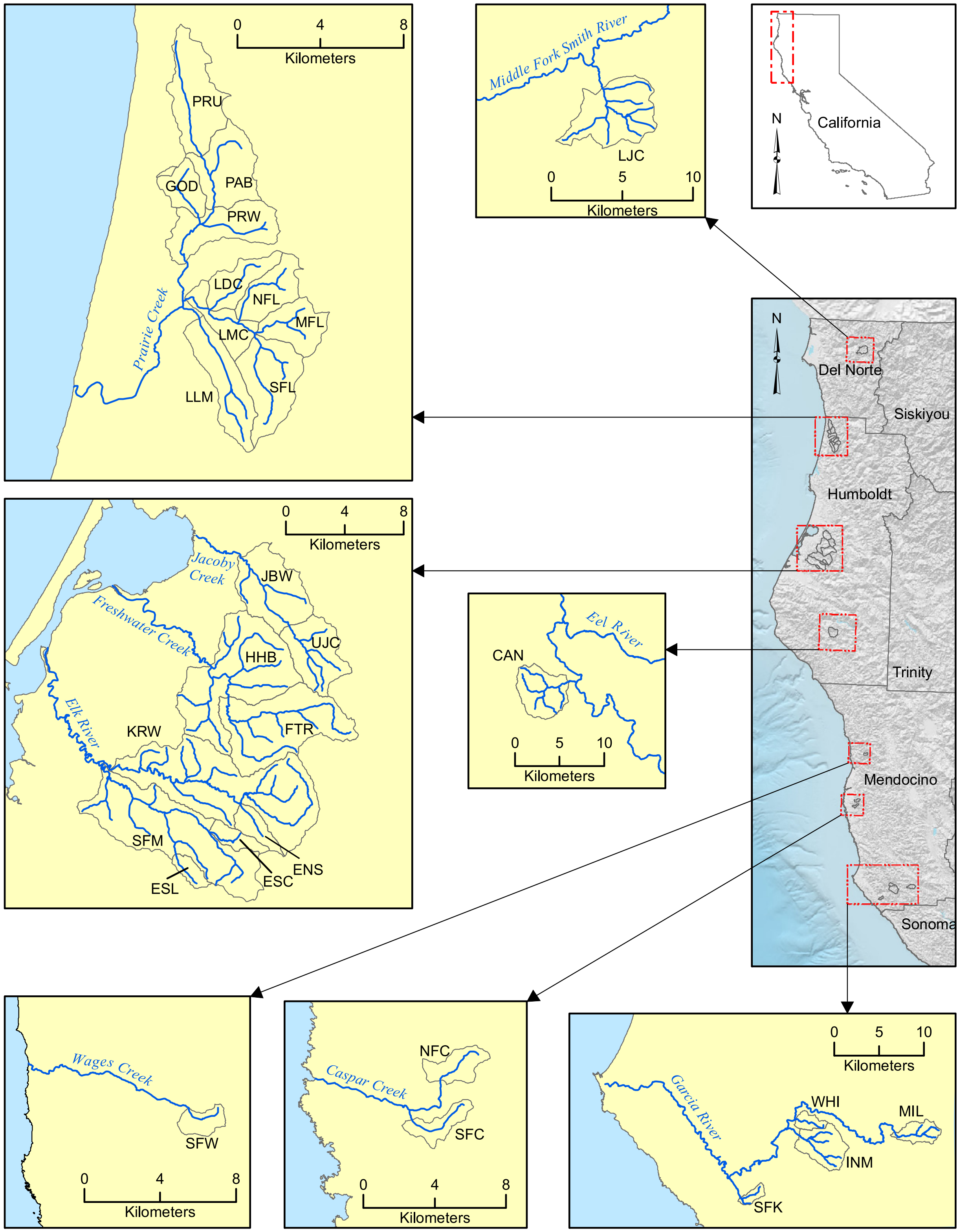

Fig. 1. Watersheds and counties in study area, north coastal California.

watershed slope and hypsometric integral (Dowling, et al., 1998) and for input to SINMAP (Pack et al., 1998), a slope stability modeling program that outputs 'stability index,' or factor of safety (FS), map data indicating areas of relatively high likelihood of shallow debris slides. Road and stream data were also obtained from the U.S. Geological Survey. THP data files were obtained from the California Department of Forestry and Fire Protection and included harvest acreages and road data from within harvest areas. These data were used in regression analyses with WY2005 10%TU as the dependent variable to determine which were the best predictors of chronic turbidity.

Different types of timber harvest impose different disturbance levels per unit area of harvest, with clearcut harvest and tractor yarding (still widely used) creating most disturbance. Consequently, harvest areas were weighted by the silvicultural method according to

Please cite this article as: Klein, R.D., et al., Logging and turbidity in the coastal watersheds of northern California, Geomorphology (2011), doi:10.1016/j.geomorph.2011.10.011

Table 1
Attributes of streams and watersheds used in this study.

Stream [a]	Site Code	Harvest Catergory	Drainage area (km^2)	Mean basin slope (%)	Basin relief (m)	Mean annual precip.[b] (mm)	Data period WY
Whitlow Creek	WHI	High	4.9	41	427	1400	2004–05
S Branch NF Elk River	*ENS*	High	4.9	31	518	1400	2004–05
North Fork Elk River	*KRW*	High	57.4	35	701	1400	2003–05
Inman Creek	INM	High	19.5	43	579	1400	2005
Corrigan Creek	*ESC*	High	4.1	33	396	1400	2004–05
South Fork Elk	*SFM*	High	50.0	30	610	1400	2004–05
North Fork Caspar Creek	NFC	High	4.8	36	244	1400	2003-05
Freshwater Cr at HH Bridge	*HHB*	High	72.8	32	671	1400	2005
Lower Jacoby Creek	*JBW*	Low	35.1	32	640	1400	2003–05
Upper Jacoby Creek	*UJC*	Low	15.1	38	488	1400	2003–05
Freshwater Creek at Roelofs	*FTR*	Low	33.1	38	853	1400	2004–05
Mill Creek	MIL	Low	9.4	39	305	1400	2004–05
SF Wages ab Center Gulch	SFW	Low	2.9	58	488	1400	2004–05
South Fork Caspar Creek	SFC	Low	4.1	33	305	1400	2003–05
South Fork Garcia R	SFK	Low	3.5	45	579	1400	2005
Prairie Cr above May Cr	*PRW*	Legacy	33.4	29	549	1650	2004–05
South Fork Lost Man Creek	*SFL*	Legacy	10.2	39	610	1650	2003–05
Lost Man Creek at Hatchery	*LMC*	legacy	31.3	30	427	1650	2003–05
Middle Fork Lost Man Creek	*MFL*	Legacy	5.8	36	518	1650	2004–05
North Fork Lost Man Creek	*NFL*	Legacy	5.8	34	488	1650	2004–05
Larry Damm Creek	*LDC*	legacy	4.8	26	488	1650	2004–05
Little Jones Creek	LJC	Legacy	22.3	51	945	2670	2003–05
Canoe Creek	*CAN*	Legacy	26.2	43	975	2670	2004–05
Little South Fork Elk River	*ESL*	pristine	3.1	23	244	1400	2004–05
Godwood Creek	*GOD*	Pristine	3.8	29	213	1650	2003–05
Little Lost Man Creek	*LLM*	Pristine	9.1	29	640	1650	2003–05
Prairie Cr above Boyes Cr	*PAB*	Pristine	19.9	31	427	1650	2004–05
Upper Prairie Creek	*PRU*	Pristine	10.8	29	396	1650	2003–05

[a] Humboldt County subset streams appear in *italics*.
[b] From isohyetal maps at: http://frap.cdf.ca.gov/webdata/maps/statewide/rainmap.pdf.

state guidelines (NCRWQCB, 2006) to account for varying levels of ground disturbance and potential water quality impacts. Weighting of the silvicultural prescription ground surface areas by the values listed in Table 3 reduced the effective areas of lower disturbance types, and resultant harvest rate variables were expressed as 'clearcut equivalent area.' Harvest, yarding, and road building data up to 15 years (1990–2004) prior to the turbidity measurements (WY2005) were assembled from timber harvest plan records kept by the California Department of Forestry and Fire Protection. This period was broken into three 5-year subperiods (see Table 2) to explore the relative importance of harvest age. Clearcut equivalent harvest rate was expressed as the annual mean 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 for WY2005 among the watersheds since this water year had most stations. Regressions were performed on two groups: (i) all streams and (ii) a subset of streams loosely clustered in Humboldt County, CA. Regressions initially used 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. When no further improvement was possible by adding variables, improvement was sought by substituting highly correlated predictors for one another. The primary diagnostic for evaluating model improvement was the corrected Akaike's Information Criterion (AIC_c) (Burnham and Anderson, 2002). The best model was considered to be the one that minimized the AIC_c. Because a wildfire severely burned nearly 75% of Canoe Creek (CAN) in 2003 (Scanlon, 2007) just prior to the turbidity records used here, this watershed was omitted from the regression analyses.

We considered it important to investigate whether we might be overfitting our data in the regression analysis by having the luxury of selecting among 30 predictors: if one has enough random variables, a 'good' relationship can always be found between the predictors and the response variable. So, a permutation test (Good, 2005) was performed by randomly reassigning the 10%TU (response variable) to our vector of 30 explanatory variables 1000 times and fitting a stepwise regression with two predictors to each resulting data set. The proportion of regression r^2 values at least as great as that obtained for the actual sample is indicative of whether or not our response is truly related to the predictors or whether the relationship appears significant as a result of fitting the model to noise.

As an additional test of overfitting and to determine how well the model could be expected to perform with independent data, prediction error was calculated (Efron and Tibshirani, 1993) leaving one observation out at a time. In this procedure, each observation is predicted from the regression coefficients calculated without that observation. The cross-validation prediction error is computed as the root mean square difference (RMSE) between each prediction and its observed response.

As noted earlier, some of our sites were nested within each other, raising the concern that the regression assumption of independence may have been violated. If there is such a dependency then reported *p*-values may be too low. To investigate this possibility, absolute differences between regression residuals for each watershed pair were evaluated in relation to watershed nesting factor, defined as the proportion of the larger watershed occupied by the smaller. The absolute differences were transformed as needed to normalize them for t-tests and regression. We then looked for significant differences between their means for nested and nonnested watershed pairs in the full data set and the Humboldt County subset, and examined linear regressions of the transformed differences on nesting factor. Similar residuals (i.e., smaller transformed differences) for nested or more highly nested watersheds would indicate lack of independence.

The watersheds (except Canoe Creek) were also placed into harvest rate categories, including pristine (never harvested), legacy (no harvest since 1990), low harvest (<1.4% CCE 10–15), and high harvest (≥1.5% CCE 10–15). To evaluate where legacy-harvested watersheds fall in the spectrum from pristine watersheds to those that have been intensively harvested in recent years, we performed another type of

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Table 2
Predictor variables considered in regression analyses.

Watershed variables	Units	Code
Drainage area	km^2	DRA
Mean watershed slope	Percent	AWS
Perrenial stream density	km/km^2	PSD
Intermittent stream density	km/km^2	ISD
Total stream density	km/km^2	TSD
SINMAP area with FS < 1	Percent of area	SIN < 1
SINMAP area with FS 1.0-1.1	Percent of area	SIN 1.0
SINMAP area with FS 1.1-1.2	Percent of area	SIN 1.1
SINMAP area with FS > 1.2	Percent of area	SIN > 1.2
Hypsometric integral	n/a	HYP
Basin relief	Meters	RLF
WY2005 annual precipitation recurrence interval	Years	ANP
WY2005 max. 1-day precipitation recurrence interval	Years	1DP
WY2005 max. 2-day precipitation recurrence interval	Years	2DP
WY2005 max. 3-day precipitation recurrence interval	Years	3DP
Basin-wide road characteristics		
Basin-wide road density: all roads	km/km^2	GRD
Basin-wide road density: lower slope roads	km/km^2	LSRD
Basin-wide road density: mid-slope roads	km/km^2	MSRD
Basin-wide road density: upper slope roads	km/km^2	USRD
Data from approved THPs [a]		
Clearcut equivalent area, 1990–2004	Weighted % of area	CCE 0–15
Clearcut equivalent area, 1995–2004	Weighted % of area	CCE 0–10
Clearcut equivalent area, 2000–2004	Weighted % of area	CCE 0–5
Clearcut equivalent area, 1995–1999	Weighted % of area	CCE 5–10
Clearcut equivalent area, 1990–1994	Weighted % of area	CCE 10–15
Tractor yarded area, 1990–2004 (15-yr)	Percent of area	TYA-15
Permanent roads constructed 1990–2004	km/km^2	PRC-15
Seasonal roads constructed 1990–2004	km/km^2	SRC-15
Temporary roads constructed 1990–2004	km/km^2	TRC-15
Temporary and seasonal roads constructed 1990–2004	km/km^2	TSR-15
All nonpaved roads constructed, 1990–2004	km/km^2	ARC-15

[a] THP data (road lengths, harvest, and yarding areas) are expressed on a per-unit area basis for the entire gaged watershed; clearcut equivalent area (CCE) variables are expressed on a mean annual basis.

permutation test (Good, 2005) to compare means between the legacy group and each of the other groups. For this test we utilized 2004 and 2005 data. The permutation test was selected because it is an exact, easily interpretable, nonparametric test suitable for small sample sizes, and it can be used with unbalanced repeated measures designs. The data are unbalanced because three more sites were available in 2005 ($n=27$) than in 2004 ($n=24$). And the 2004 and 2005 measurements of 10%TU for a given station are highly correlated ($r=0.96$), so they must be treated as repeated measures. For this permutation test, the group labels for any two groups being compared are reassigned to the paired (2004, 2005) turbidity values, in every possible permutation, and the 2004 and 2005 differences in mean 10%TU between the two groups are computed for each permutation. The proportion of permutations for which both the 2004 and 2005 differences equal or exceed the differences observed in the actual sample is interpreted as the probability of the observed result having occurred if group identity were unrelated to 10%TU. A small probability indicates that there is a significant relation between harvest rate and turbidity. For the comparison between legacy and pristine groups, a one-sided test was used, as the only reasonable alternative to the null hypothesis of no difference is that legacy watersheds have higher turbidity. For the comparisons between legacy and the contemporary harvest groups, two-sided tests were employed, because the relative impacts of legacy and contemporary harvesting are controversial. In the two-sided tests, the absolute values of the differences are compared rather than the raw differences.

The 10%TU represents just one point along a turbidity duration curve that we used to characterize relatively low, chronic turbidity for this analysis. As is intuitively obvious and evident from the biological literature cited above, higher turbidities can also have biological impacts. To provide a more comprehensive portrayal of the range of turbidities among the four harvest categories, we took the means of WY2005 turbidity values for the sites within each category at each probability and plotted the group mean turbidity duration curves.

4. Results

Rainfall for WY2005 was near normal at about 90% of the mean in the northern portion of the study area and slightly above normal in the southern portion. Turbidities at the 10% exceedence probability ranged from 3 to 116 FNU (formazin nephelometric units; Anderson, 2004), as shown in Table 4 along with turbidities at several other exceedence levels. The cumulative time > 25 FNU spanned a factor of 100, ranging from 15 to 1566 h, as shown in Table 4 along with cumulative hours above several other turbidity levels. Water in the most turbid streams rarely (and only briefly) fell to < 25 FNU (approximate 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 just 0–2 hours total in WY2005.

Table 5 summarizes turbidity results for the study streams (CAN omitted) for WY2004 and WY2005 grouped as harvest rate categories. Means of harvest rate, drainage area, and 10%TU are shown for each water year. The permutation tests indicated that the legacy group was significantly more turbid than the pristine group ($p=0.0088$), and less turbid than the high harvest group ($p=0.0009$), but not significantly different from the low harvest rate group ($p=0.0542$). In WY2005, mean 10%TU nearly doubled with each step upward in harvest category from pristine to high harvest; results for WY2004 showed slightly smaller increases. The 10%TU for individual sites within each category are plotted in Fig. 2 to illustrate the range of turbidities within each category, which also increases with each step upward in harvest intensity. While some legacy and low harvest sites had low turbidities (nearly as low as some pristine sites), none among the high harvest category were < 24 FNU.

Turbidity duration curves for the harvest categories are plotted in Fig. 3. As illustrated, the differences in turbidity among harvest categories extended throughout the range of recorded turbidities. Differences were large at the 10% exceedence probability and increased at lower exceedence probabilities (less frequently occurring, higher turbidities). For example, the mean for pristine streams was 36 FNU at the 1% and 113 FNU at the 0.1% exceedence levels, while the means for high harvest were 290 and 734 FNU, respectively.

The best fit from multiple regression analyses using both the full set of streams ($n=27$ with CAN omitted) and the Humboldt County

Table 3
Weighting factors for areas of silvicultural prescriptions.

Silvicultural prescription	Weighting factor
Clearcut	1.00
Commercial thin	0.50
Group selection	0.50
Rehabilitation of understocked areas	1.00
Road right of way	1.00
Sanitation salvage	0.75
Shelterwood preparation cut	0.75
Shelterwood removal cut	0.75
Shelterwood seed cut	0.75
Selection	0.50
Seed tree removal cut	0.75
Seed tree seed cut	0.75
Alternative prescription	0.75
Variable retention	0.50

Table 4
Harvest rates, turbidities at specified exceedence probabilities, and cumulative hours above specified turbidities for WY2005.

Site	Harvest rate	Turbidity (FNU) at specified exceedence					Cumulative hours above specified turbidity					
Code [a]	CCE10-15	0.1%	1%	2%	5%	10%	1000	500	200	100	50	25
SFM	2.43%	1245	551	370	185	116	11	54	195	513	936	1566
KRW	3.87%	766	376	271	161	93	1	25	157	399	810	1538
ENS	3.98%	1416	483	303	144	76	13	41	150	320	678	1290
HHB	2.20%	620	281	197	107	67	1	8	85	238	670	1413
FTR	1.10%	675	254	167	87	57	0	8	67	184	550	1363
CAN	0.00%	509	225	152	92	56	0	6	56	186	485	936
JBW	1.32%	794	307	205	96	53	1	14	90	211	470	1016
ESC	2.64%	785	249	148	78	50	1	14	56	140	440	1058
UJC	1.15%	1662	293	167	75	42	8	23	71	150	349	860
SFC	0.03%	258	110	77	48	37	0	0	10	52	197	909
NFC	2.21%	359	107	65	43	33	0	0	17	46	174	829
WHI	4.66%	416	149	92	48	29	0	2	26	78	209	552
INM	2.93%	327	127	64	40	26	0	0	24	53	138	504
SFL	0.00%	548	197	107	42	22	0	7	43	94	187	387
MFL	0.00%	590	157	87	40	21	0	8	32	76	172	379
LMC	0.00%	494	131	72	33	18	0	4	27	62	136	317
MIL	0.18%	235	99	73	34	18	0	0	6	43	140	308
NFL	0.00%	343	145	79	36	18	0	0	29	67	150	322
LDC	0.00%	213	106	66	31	16	0	0	7	48	120	278
LLM	0.00%	256	77	47	26	16	0	0	11	32	78	227
PRW	0.00%	290	94	55	26	14	0	0	11	38	98	229
ESL	0.00%	79	31	22	16	12	0	0	0	2	15	71
SFK	0.01%	259	71	45	20	11	0	0	10	24	76	180
PRU	0.00%	81	26	17	10	6	0	0	0	1	16	45
GOD	0.00%	66	23	16	9	6	0	0	0	0	12	34
LJC	0.00%	41	25	14	8	5	0	0	0	0	0	46
SFW	0.07%	60	15	10	6	4	0	0	0	0	7	16
PAB	0.00%	82	24	14	6	3	0	0	0	1	14	41

[a] See Table 1 for corresponding stream names; *italics* indicates Humboldt County streams; data in bold are pristine sites.

subset ($n = 19$ with CAN omitted) included just two explanatory variables: clearcut equivalent area for the period 10–15 years before the WY2005 turbidity record (1990–1994) and drainage area. Clearcut equivalent area was highly significant ($p < 0.0002$) in both models. Drainage area was highly significant ($p = 0.0013$) in the full set model, but less so ($p = 0.018$) in the Humboldt County set. The full set model resulted in an RSE (residual standard error) of 17.5 and adjusted multiple r^2 of 0.63. Other models using just harvest rate (including annual mean harvest rate 0–15 years 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 RSE of 13.7 and adjusted multiple r^2 of 0.82. A comparison of observed and predicted 10%TU from these regressions (Figs. 4 and 5) illustrates the lower variance for the Humboldt County set and shows that nearly all streams conform fairly well to the models. The most significant outlier in both models is South Fork Elk River (SFM), which lies mainly in the Wildcat Formation, a highly erodible geologic unit formed largely from poorly consolidated Tertiary alluvial sediments.

In the permutation tests for regression overfitting, out of 1000 stepwise regressions on data sets with randomly shuffled responses, only one had an r^2 (0.672) exceeding that of the observed full data

Table 5
Turbidities of harvest rate category group means for WY2004–2005 and permutation test p-values.

Harvest category	Harvest rate	Drainage area (km^2)	WY2005 10%TU (FNU)	WY2004 10%TU (FNU)	Permutation Test p-value
High	3.1%	27.3	61	52	0.001
Low	0.6%	14.7	32	26	0.054
Legacy	0.0%	16.2	16	16	N/A
Pristine	0.0%	9.3	8	6	0.009

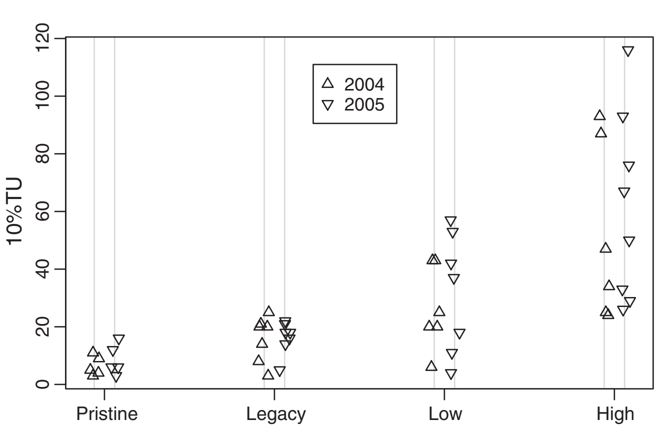

Fig. 2. 10%TU for study sites grouped by harvest rate category.

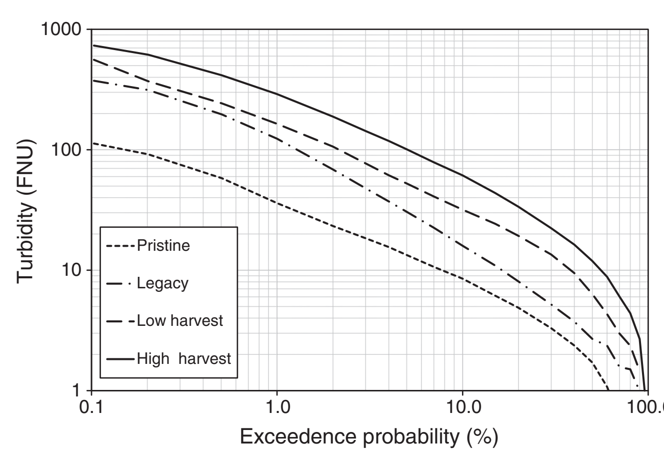

Fig. 3. Turbidity duration curves for WY2005 for four harvest rate categories.

Please cite this article as: Klein, R.D., et al., Logging and turbidity in the coastal watersheds of northern California, Geomorphology (2011), doi:10.1016/j.geomorph.2011.10.011

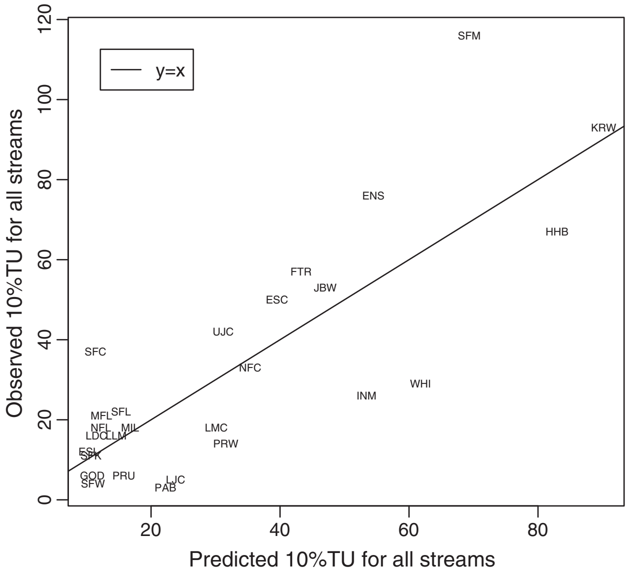

Fig. 4. Observed 10%TU values for 27 streams (excludes Canoe Creek) compared to those predicted by regression on drainage area and clearcut equivalent area for the period 10–15 years before the WY2005 turbidity record.

set (0.660). For the Humboldt County subset, none of the 1000 regressions produced an r^2 exceeding that of the observed data (0.842). The highest r^2 for the permuted Humboldt data sets was 0.784. These tests indicate an underlying relationship between our predictors and 10%TU (and drainage area) that is not a fortuitous result of the number of explanatory variables considered.

Cross-validation prediction error, leaving out one observation at a time from the full data set ($n=27$), was 23.6 FNU for the regression model without drainage area, compared with 20.3 when drainage area was included and 16.5 for the regression on the full data set. These results support the inclusion of drainage area in the model but indicate a bias of 3.8 FNU in the RMSE of the unvalidated two-variable model. For the Humboldt County data set, the corresponding prediction errors were 17.6, 15.7, and 12.6, again supporting the inclusion of drainage area and indicating a bias of 3.1 FNU in the RMSE of the unvalidated two-variable model. Such bias in estimated prediction error is to be expected with small data sets such as these.

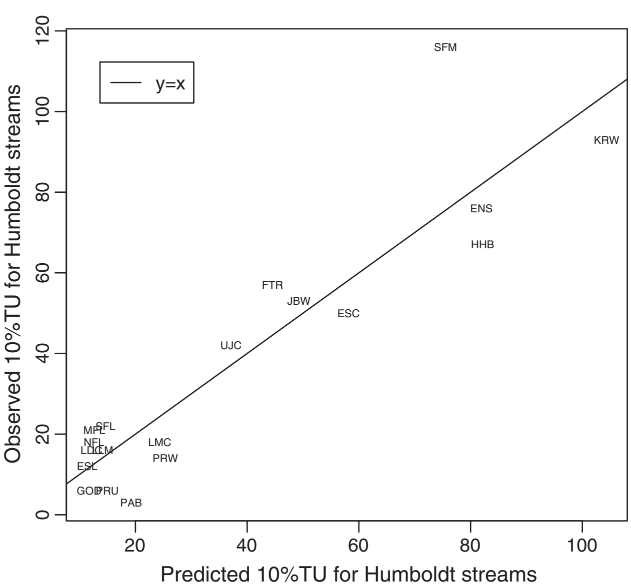

Fig. 5. Observed 10%TU values for 19 Humboldt county streams (excludes Canoe Creek) compared to those predicted by regression on drainage area and clearcut equivalent area for the period 10–15 years before the WY2005 turbidity record.

The tests for independence of nested watersheds revealed no significant difference between the means of the transformed differences for nested and non-nested watershed pairs for the full data set ($p=0.97$) or the Humboldt County subset ($p=0.80$). A cube root transformation was found to best normalize the absolute differences between residual pairs. Linear regressions of the transformed differences on nesting factor were also not significant ($p=0.33$ full data set, $p=0.69$ Humboldt County subset). Lack of independence would have to be very marked to invalidate the highly significant regression results for harvest rate, and there is scant evidence in our data that nested watersheds were correlated.

5. Discussion

The rate of timber harvest, expressed as mean annual clearcut equivalent area for the period 10–15 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 suggest the importance of rate of timber harvest and were consistent with the earlier results of Klein (2003) in a similar study, for which fewer sites were available.

Basin geomorphic characteristics reflect basin-shaping processes and susceptibility to erosion-accelerating disturbances. To account for this, several variables (e.g., watershed slope and relief, stream density, SINMAP shallow landsliding potential) 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, geography was used to reduce natural variability and regression results were improved.

Contrary to our expectations, some research results (Anderson, 1970, 1975, 1979; Reid and Dunne, 1984), and conventional wisdom, road variables added little 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 underrepresented in 'off-the-shelf' data sets used here. 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 typically rise with increasing harvest rate. The correlations in the full data set were $r=0.80$ ($n=28$, $p<0.001$) between 15-year mean annual harvest rate and basin-wide road density and were $r=0.70$ ($n=28$, $p<0.001$) between mean annual harvest rate and nonpaved road construction in the 15 years prior to the turbidity data period (WY2005).

Large differences were observed in WY2004-2005 turbidities at the 10% exceedence level between managed watersheds and background levels exhibited by pristine streams. Even streams with no harvest in the prior 15 years, legacy sites, as a group, would have been far out of compliance with the regulatory limit for northern California streams: "Turbidity shall not be increased more than 20% above naturally occurring background levels" (NCRWQCB, 2011, p. 3–3.00). Individually, all but two actively harvested watersheds would have been out of compliance with this standard in WY2005, a relatively normal hydrologic year. We note that extremely destructive harvesting prior to implementation of California's forest practice rules in about 1980 (legacy effects) is a likely contributor to 10%TU in all but the pristine category of our watersheds. Legacy harvest erosional features are often cited as primarily responsible for persistent turbidity impairment in actively harvested watersheds, but our data suggest this is only partly true. As shown in Table 5, the mean 10%TU for the low harvest group was twice that of the legacy group (though the difference was not statistically significant), and the mean for the high harvest group was nearly four times that of the legacy group. Thus, the extent of water quality degradation in actively harvested watersheds, wherein modern BMPs are used, cannot be solely attributed to residual effects of more destructive harvesting practices of the past. In fact, modern logging practices appear to be the dominant factor, with turbidity impairment rising with increasing rate of harvest.

The fact that clearcut equivalent area for the period 10–15 years preceding the turbidity dataset was the best predictor of chronic turbidity suggests that harvesting could have much larger impacts and last for much longer time periods than in the paired watershed studies cited by Gomi et al. (2005). One reason for this lag time in harvest effects may be the role of root biomass and decay following harvest (Burroughs and Thomas, 1977; Ziemer, 1981). With respect to the redwood-dominated forests of our analysis, previous work (Ziemer and Lewis, 2006, unpublished) indicated that live redwood root mass declined rapidly for the first few years before starting to increase again, while dead root mass increased for 5–10 years before declining. Total root biomass reached a minimum at 10–15 years after harvest in redwood forests, declining slower and to a lesser degree than in the mixed conifer forests studied earlier by Ziemer (1981). The 15-year harvest period we considered likely encompassed root-strength minimums for harvest that took place in the beginning of the period. Although storm sequence is important too, landslides have the highest risk of occurring when the soil shear strength from roots reaches a minimum. Thus, a decade or more after harvest may be required before harvest-related landslides occur and elevate sediment production and turbidity. Logging appears to have increased the incidence of large landslides in the North Fork Caspar watershed. In 35 years of monitoring the North Fork Caspar Creek, the three largest landslides (1700–2600 m^3) all occurred on clearcut hillslopes 15, 12, and 10 years after harvesting (Reid, in press).

Compounding the loss of root strength following harvesting are the increased pore water pressures that must result from reductions in interception and transpiration. Reid and Lewis (2009) measured mean interception loss rates of 21% during large winter storms in the second-growth redwood and Douglas-fir stands of North Fork Caspar Creek. The corresponding increase in effective rainfall reaching the forest floor was 27%. Elevated soil moisture levels might last only a decade or so without further silvicultural treatments, but subsequent burning, herbiciding, and thinning is typical in many areas and can prolong or renew hydrologic changes (e.g. Keppeler et al., 2003). In addition to increasing the potential for landsliding, as Reid et al. (2010) showed, gullies may form or enlarge a decade or more following harvest within clearcut units because of elevated soil water. Thus, even in the absence of logging roads, sediment delivery through landsliding and gully erosion can impair downstream water quality long after an area is logged.

The crude weighting factors in Table 3 may not properly reflect relative changes in hillslope hydrology and root strength. For example, in second-growth redwood forests which have regenerated largely by root sprouting, groups of trees often share a common root system. When the forest is reharvested selectively, residual trees may be able to access harvested trees' root systems for water uptake, growing rapidly when the canopy is opened up, and resulting in less root dieback and more efficient water utilization than an 'equivalent' clearcut (Reid and Lewis, 2011). Further, since a given silvicultural method can be applied at varying intensities, a system that takes into account the proportion of basal area or wood volume removed from harvested areas would likely perform better than the blanket weightings used in this analysis.

Because they intersect frequently on the landscape, logging road stream crossings are perhaps the most prominent sources of delivery of sediment to streams. Erosion from within cut units is less likely to reach a stream, depending on site topographic and hydrologic attributes and the effectiveness of streamside buffers. Although buffers are a commonly applied BMP that limit the occurrences or volumes of sediment from reaching a channel, instances of 'break-through' (hillslope-eroded sediment passing through a buffer) can occur nonetheless, as we have observed in the field. Rivenbark and Jackson (2004) documented one breakthrough occurrence for about every 8 ha of clearcut forestlands in the southeastern U.S., with 14% of the 187 breakthroughs inventoried traveling > 30 m before reaching a stream channel.

We observed differences among geographically separated clusters of our data set. One noticeable trend was that watersheds in Mendocino County had lower turbidities, despite having relatively high harvest rates in some cases (particularly Inman and Whitlow Creeks; Table 4). One reason for this trend may be that winter operations are less prevalent in Mendocino County than in Humboldt County. Conducting timber operations during winter greatly increases the potential for sediment delivery because of the erosional effects of rainfall and runoff energy on freshly disturbed ground and log hauling on unsurfaced and poorly engineered roads. Furthermore, highly erodible soils, such as those formed on the Wildcat Formation in Humboldt County, have naturally greater turbidity levels and are particularly susceptible to land use disturbances.

6. Conclusions

Although the rate of timber harvest has been acknowledged among scientists, regulatory agencies, and legislators as a factor contributing to declining water quality and aquatic habitat for some time, regulatory controls on harvest rate do not presently exist. Instead, the regulatory community has largely relied on site-specific best management practices (BMPs) to attempt to maintain water quality. In a compilation of information on BMP programs for states in the Western U.S., the Council of Western State Foresters (2007) reported that compliance with BMPs, where quantified, was mixed. And although BMP effectiveness monitoring projects exist in several western states, little in the way of published results was found. Certainly BMPs have helped reduce site-specific erosion and resultant turbidity and suspended sediment impacts from timber harvest, but they are neither perfectly conceived nor perfectly implemented. Consequently, severe degradation of water quality can occur despite use of BMPs in watersheds where too much of the land base is harvested over too short a time period.

Contemporary erosion prevention treatments for logging roads (e.g., decommissioning of abandoned roads, 'storm-proofing' actively used roads) have greatly reduced threats to downstream water quality, but other factors contributing to cumulative watershed effects remain unaddressed. Current BMPs do not address the effects of tree removal on hillslope hydrologic changes and loss of root strength from decay. However, limiting the rate of harvest in erosion-prone terrain, perhaps in the form of new BMPs, could do much to close the gap between what regulatory programs desire to achieve and actual water quality conditions in streams.

Managing cumulative watershed effects requires a working, continually updated knowledge of the complexities of natural and anthropogenic factors and their interactions operating on a watershed scale, but such a process continues to elude regulatory institutions. Thirty years ago, Coats and Miller (1981) outlined the primary obstacles to that end and proposed several solutions, including a 'watershed information systems' approach to provide the knowledge base for cumulative effects management. Since then, technological advances in geographic information systems (GIS) make this approach more feasible. Whatever the tool applied, unless and until a watershed approach is taken that addresses the full spectrum of potential effects of timber harvesting, high levels of chronic turbidity will continue to impair salmonid populations and other aquatic biological resources in working forestlands.

Acknowledgments

The authors appreciate turbidity data contributions from the U.S. Forest Service Redwood Sciences Laboratory in Arcata, CA, the nonprofit group Salmon Forever, hydrologists Peter Manka and Terry Jo Barber (and her client, Mendocino County Resource Conservation District), Campbell Timber Company, and support from Redwood National and State Parks in operating turbidity stations in the Prairie Creek watershed. Adona White of the California North Coast Regional Water Quality Control Board secured and provided funding and logistical support for the project on which this paper is based.

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