

Turbidity and Total Suspended Solid Concentration Dynamics in Streamflow from California Oak Woodland Watersheds¹

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Abstract

Resource agencies, private landowners, and citizen monitoring programs utilize turbidity (water clarity) measurements as a water quality indicator for total suspended solids (TSS – mass of solids per unit volume) and other constituents in streams and rivers. The dynamics and relationships between turbidity and TSS are functions of watershed-specific factors and temporal trends within storms and across seasons. This paper describes these relationships using four years of water quality and stream discharge data from seven experimental watersheds in the northern Sierra foothills and north coast oak woodlands of California. Rating curves predicting TSS concentration as a function of turbidity were developed with simple linear regressions. Stream discharge rapidly rose and fell in response to winter storms once watershed soils were saturated. Turbidity and TSS concentrations paralleled this seasonal rise and fall in stream discharge. In addition, a hysteresis effect was observed for both TSS and turbidity during individual storms. Regression slopes for TSS versus turbidity were significantly different between watersheds of similar and differing soils, geology, and hydrology. These results indicate the need for intensive, storm-based sampling to adequately characterize TSS and turbidity in oak woodland watersheds. Water quality monitoring programs that account for the watershed specific nature of turbidity and TSS relationships and the influence that climate, soils, geology, and hydrology have on these relationships will better represent water quality and sediment transport in California oak woodland watersheds.

Introduction

California's oak woodland watersheds provide important ecologic and hydrologic functions. In many cases these watersheds are headwater tributaries for larger river basins and as a result, the quality of water being released from these catchments impacts those watershed functions. For example, increased suspended sediment and turbidity can directly impact aquatic organisms (Sigler and others

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1984), alter stream grade, contribute to flooding, and transport a large nutrient flux. Resource agencies and community based resource management programs are developing and implementing watershed management plans to reduce sediment inputs and improve water quality in response to these impacts (CRWQCB 1998).

While site-based erosion inventory and assessments (Lewis and others 2001) are effective means of identifying and mitigating specific sediment sources, in-stream sediment concentration and yield monitoring are important in determining the overall effectiveness of these watershed management efforts. Turbidity has been identified as an effective and inexpensive indicator of suspended sediment (Lewis 1996, Walling 1977). Strong relationships between TSS and turbidity have been repeatedly and consistently identified (Gippel 1995). Turbidity is less expensive and more easily measured than TSS. This provides for the high sampling frequency needed to account for temporal variability in TSS concentrations (Tate and others 1999). For these reasons, turbidity is being promoted as a key parameter for monitoring activities by resource agencies and community-based watershed groups. In order for turbidity to serve as a surrogate for TSS, a numerically defined relationship for predicting TSS as a function of turbidity must be developed from data sets with paired measurements of the two parameters. The objective of our study was to utilize data from seven experimental oak woodland watersheds to: 1) document temporal dynamics of TSS and turbidity; 2) develop relationships for turbidity and TSS for each watershed; and 3) compare TSS and turbidity relationships of each watershed to determine if this changes from watershed to watershed.

Methods

Site Description

The University of California Rangeland Watershed Program began a long-term, watershed scale examination of range management effects on plant community dynamics, hydrology, nutrient cycling, and water quality in 1997. This work was conducted in a network of experimental watersheds at the University of California's Hopland Research and Extension Center (HREC) and Sierra Foothill Research and Extension Center (SFREC) (*fig. 1*).

The Sierra Foothill Research and Extension Center is located 19 miles east of Marysville, California in the northern Sierra foothills of Yuba County (*fig. 1*). Elevation ranges from 220 to 2,020 feet (67 to 616 m) and mean annual precipitation is 28 inches (71.1 cm) and ranged from 29 to 52 inches (73.7 to 132.1 cm) during the period of this study (SFREC precipitation records). Water quality and stream discharge monitoring were initiated on three instrumented watersheds (1, 2, and 3) in 1997. Watersheds 1, 2, and 3 are 35, 80, and 116 acres (14.2, 32.4, and 47.0 ha), respectively, and have been managed solely for light to moderate beef cattle grazing since 1965. Watershed soils are formed on basic metavolcanic (greenstone) bedrock (Beiersdorfer 1979) and are Fe-oxide rich, making them resistant to erosion. Soils are classified as Ruptic-lithic Xerochrepts on steep side slopes and Mollic Haploxeralfs on more level areas (Lytle 1998). Vegetation is dominated by blue oaks (*Quercus douglasii*) and intermixed with interior live oaks (*Q. wislizeni*) and foothill pine (*Pinus sabiniana*), typical of Sierra foothill oak woodlands (Griffin 1977). The uneven distribution of trees creates a mosaic of open grasslands, savanna, and woodlands (Epifanio 1989, Jansen 1987).

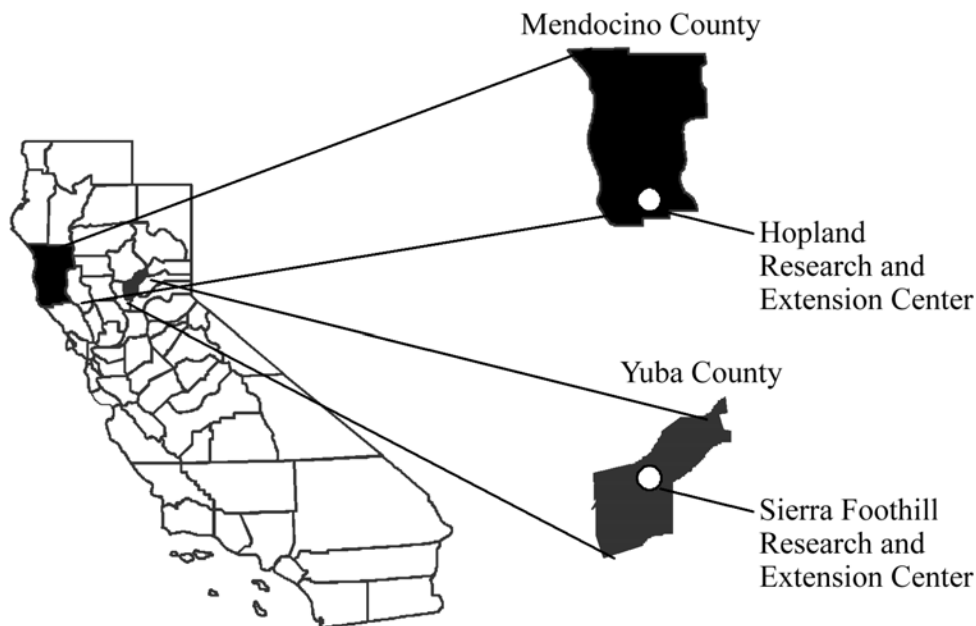


Figure 1—Location of experimental watersheds at Hopland and Sierra Foothill Research and Extension Centers.

The Hopland Research and Extension Center is located 5 miles east of Hopland, California in Mendocino County (*fig. 1*). Elevation ranges from 440 to 2,670 feet (134 to 814 m) with mean annual precipitation ranging from 37 to 45 inches (94.0 to 114.3 cm) as a function of elevation. During the period of this study, precipitation in the experimental watersheds ranged from 32 to 55 inches (81.3 to 139.7 cm) (HREC precipitation records). Geologically, the area is part of the Franciscan Formation, a mélange of fractured and jointed sandstone and shale (Burgy and Papazafiriou 1974, Gowans 1958). Soils are classified as Typic Agrixerolls and Typic Haploxeralfs (Howard and Bowman 1991). These erosive sedimentary materials and soils are typical of the coastal mountain range. Four experimental watersheds (A, B, C, and D) were established at HREC in 1998. Watersheds A and B are 29 and 22 acres (11.7 and 8.9 ha), respectively, and managed for light to moderate sheep grazing from January to March. Watersheds C and D are 56 and 20 acres (22.7 and 8.1 ha), respectively, and have been excluded from livestock grazing since 1951. The coastal oak-woodland vegetation in these watersheds is a mosaic of open grassland and oak trees comprised of valley oak (*Q. lobata*), black oak (*Q. kelloggii*), coastal live oak (*Q. agrifolia*), blue oak (*Q. douglasii*), and madrone (*Arbutus menziesii*) (Pitt 1975).

Data Collection and Analysis

Stream flow was monitored at flumes installed at the outlet of each watershed. Stage height was measured and recorded on 15-minute intervals using an electronic stage sensor. Stream water samples were collected every 1 to 2 hours during storm events using automatic pump samplers, and every 2 to 3 days during baseflow using grab samples. Data presented in this paper span three water years for HREC (1998-

2001) and four water years for SFREC (1997-2001). A water year begins on October 1 of one year and ends on September 30 of the following year.

For this study, water samples were analyzed for total suspended solids (TSS) and turbidity. Total suspended solids is a parameter used to measure water quality as a concentration (weight of solids/volume of water; mg/L) of mineral and organic sediment. We determined TSS by measuring the weight of dry solid material remaining after vacuum filtration of a known sample volume (50 to 100 mL). Samples were filtered through a 0.45-micron filter in accordance with American Public Health Association protocols (Clesceri and others 1998).

Turbidity is the measurement of water clarity measured as the amount of light that is scattered and absorbed as it passes through a water sample. It is measured with nephelometry methodology and recorded in nephelometric turbidity units (ntu) (MacDonald and others 1991). The amount of light scattered or absorbed changes as a function of the size, shape, surface characteristics, and quantity of particles within the sample (Clifford and others 1995, Gippel 1995). We analyzed samples according to American Public Health Association protocols (Clesceri and others 1998).

Rating curves for TSS as a function of turbidity were developed using linear regression methods with TSS as the dependent variable and turbidity as the independent variable. This analysis does not account for the recognized non-normal distribution of water quality data and the potential need to transform these data. However, watershed groups and other potential generators and users of such data often use simple linear regression; thus, this approach is relevant to their implementation and interpretation of TSS and turbidity relationships.

Curves for each individual watershed, as well as curves for the pooled data from each study site, were developed. The correlation coefficient for these curves indicates the variability between turbidity and TSS across a range of values. Higher correlation coefficients are indicative of lower variability and better prediction of TSS by turbidity. In addition, these curves describe the rate that TSS changes with changes in turbidity through the slope of the regression line. If watersheds have similar TSS and turbidity relationships their rating curve slopes will be similar or homogeneous. Tests of regression line slope homogeneity were made with an F-test (Snedecor and Cochran, 1989) to determine differences of intra- (within sites) and inter- (across sites) watershed TSS and turbidity dynamics. All statistical analyses were conducted utilizing SYSTAT version 9.0 (SPSS Inc., Chicago, IL).

Results

Streamflow in these intermittent streams has three distinct seasonal periods described by Huang (1997) as wetting, saturation, and drying. The 1999-2000 annual hydrographs for Watershed C at HREC and Watershed 2 at SFREC illustrate hydrological and sediment dynamics typical of the watersheds from each site (*figs. 2a,b and 3a,b*). Discharge was low and constant during the early months of winter. During this priming phase, precipitation infiltrated and recharged watershed soils and did not contribute to noticeable increases in streamflow. Streamflow responses to rainfall became elevated and rapid once soil water storage capacity was approached and the soils were saturated. Results from long-term monitoring indicate that this saturation phase was reached after six to eight inches (15.2 to 20.3 cm) of annual cumulative rainfall have occurred at SFREC (Lewis and others 2000) and eight to ten

inches (20.3 to 25.4 cm) at the HREC. Air temperature and evapotranspiration increased and storm frequency and intensity decreased with the onset of spring, resulting in a drying phase in which streamflow gradually declined. Storms during this phase generated increased streamflow, but peak stormflow was less than during the saturation phase.

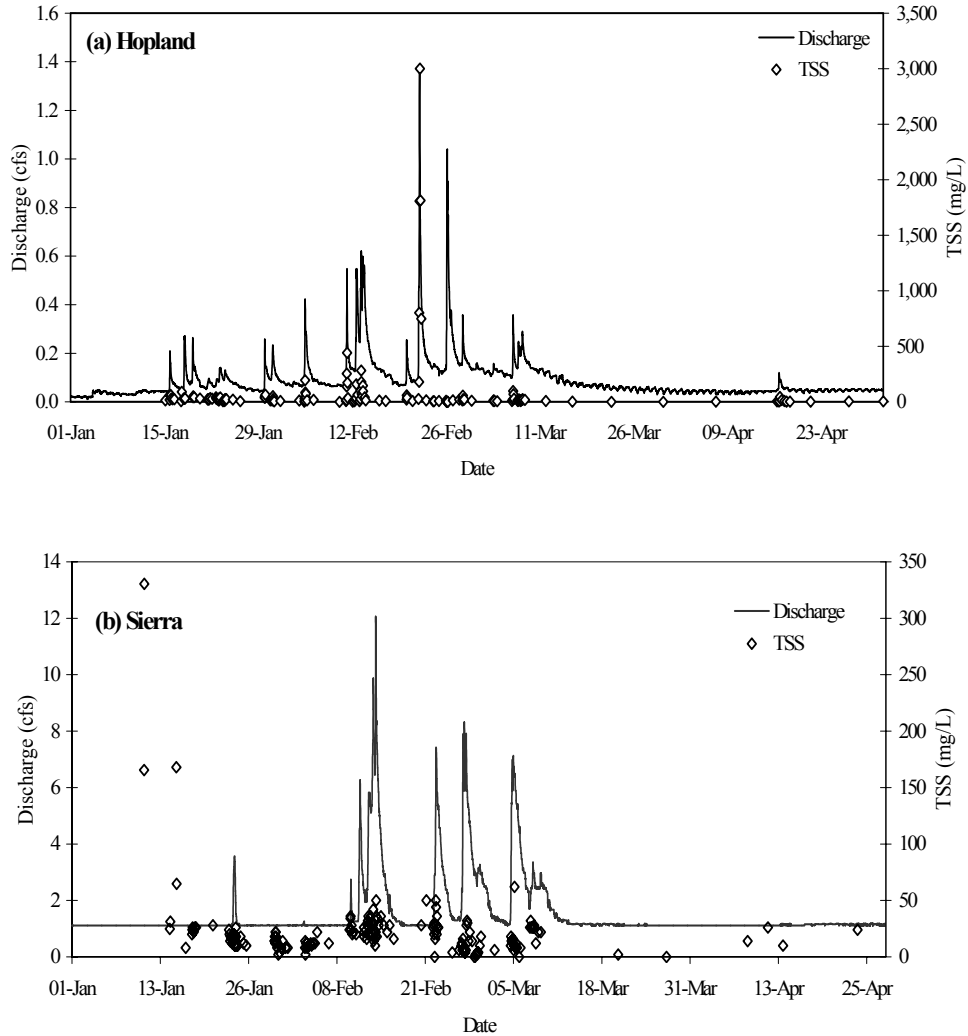


Figure 2—Total suspended solids and stream discharge for 1999-2000 in (a) Hopland Watershed C and (b) Sierra Foothill Watershed 2.

These streamflow phases resulted in seasonal variability in TSS (*figs. 2a,b*) and turbidity (*figs. 3a,b*). Both TSS and turbidity increased during the transition from wetting to saturation phases. During the drying phase, TSS and turbidity returned to the lower values observed during the wetting phase. Storm variability was also evident for TSS and turbidity (*fig. 4*). Once in the saturation phase, TSS concentrations and turbidity increased and decreased with the rise and fall of streamflow. Tracking the succession of TSS and turbidity measurements through an

individual storm as a function of discharge, it becomes evident that they increased and decreased with similar changes in discharge (*fig. 5*). Furthermore, higher TSS and turbidity values are observed on the rising limb of the hydrograph as compared to similar discharge values on the falling limb, a phenomenon termed hysteresis.

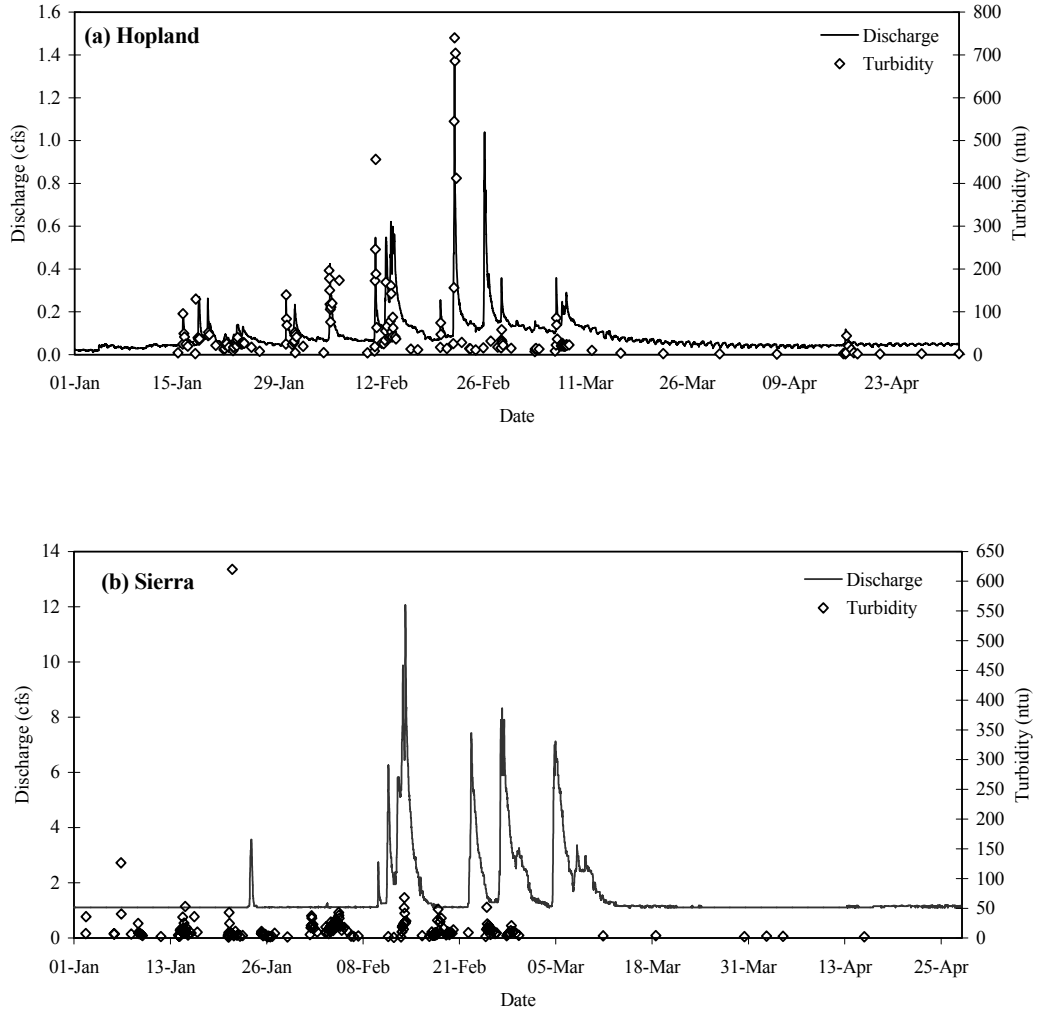


Figure 3—Turbidity and stream discharge for 1999-2000 in (a) HREC Watershed C and (b) Sierra Foothill Watershed 2.

Mean turbidity and TSS concentrations were generally higher for HREC watersheds than for SFREC watersheds (*table 1*). In addition, variability in both mean TSS and turbidity was higher within the HREC watersheds than in the SFREC watersheds, although, these differences and variability were not always statistically significant. For example, mean TSS concentration from HREC Watershed B was not significantly greater than mean TSS concentration in either SFREC Watersheds 1, 2,

or 3. And TSS concentration in SFREC Watershed 3 was not significantly less than values observed in HREC Watersheds A, B, C, or D. The mean TSS and turbidity values for the three SFREC watersheds were not significantly different. By contrast, mean TSS concentration and turbidity in HREC Watershed A were significantly greater than they were in Watersheds B and D.

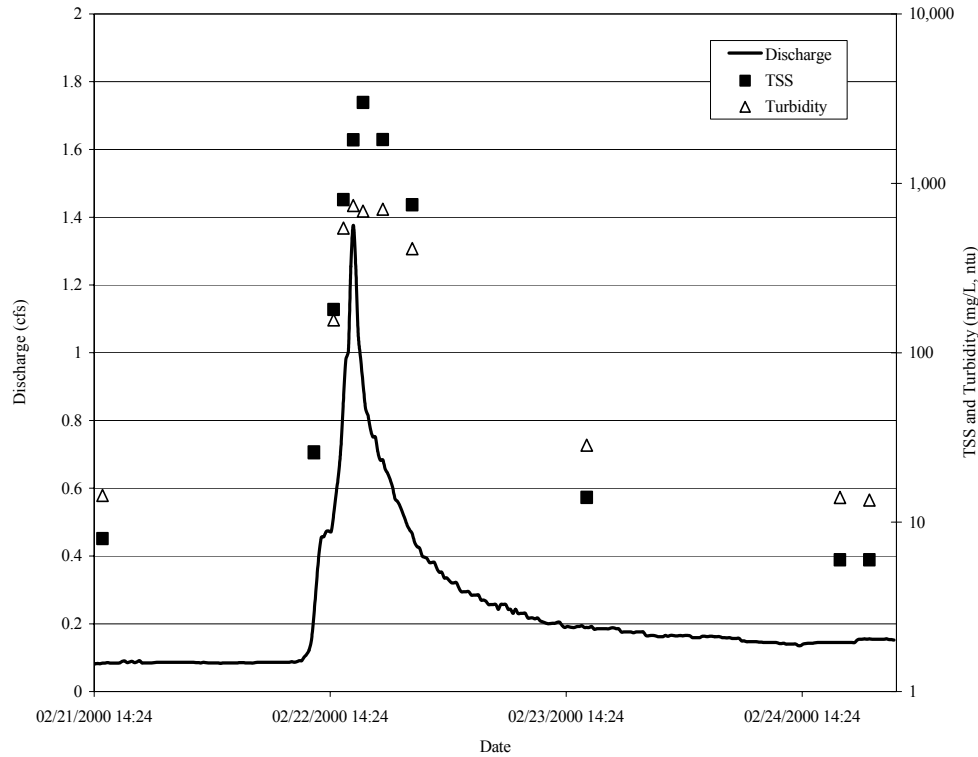


Figure 4—Effect of February 21-24, 2001 storm discharge on total suspended solids (mg/L) and turbidity (ntu) in Hopland Watershed C.

Table 1—Comparison of total suspended solids (TSS) and turbidity in Hopland (1998-2001) and Sierra Foothill (1997-2001) Research and Extension Center watersheds. Values are means \pm standard error of means. Means with different letters are significantly different ($p < 0.05$) within columns.

Site	Watershed	N	TSS mg/L	Turbidity ntu
Hopland	A	396	99.7 \pm 9.4a	66.8 \pm 5.2a
	B	344	47.6 \pm 9.8bc	29.3 \pm 3.1bc
	C	366	71.7 \pm 11.5ac	61.1 \pm 5.9a
	D	268	59.7 \pm 5.1c	51.7 \pm 4.1a
	Combined	1,374	71.5 \pm 4.9d	53.1 \pm 2.5d
Sierra	1	309	22.2 \pm 1.2b	25.3 \pm 1.4bc
	2	372	24.5 \pm 1.7b	18.2 \pm 2.0b
	3	350	46.3 \pm 3.3bc	38.5 \pm 2.5c
	Combined	1,031	31.2 \pm 1.4 e	27.2 \pm 1.2e

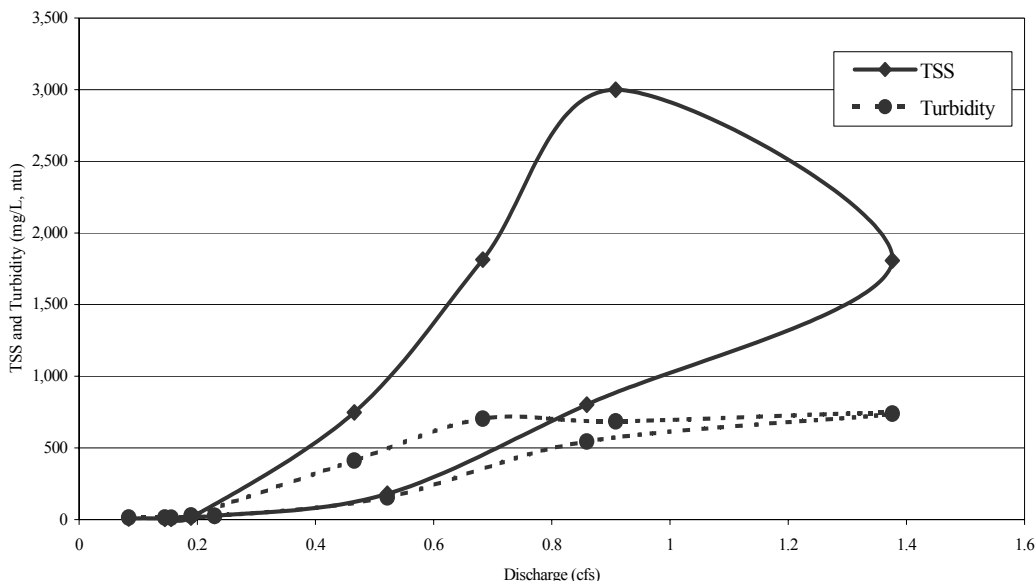


Figure 5—Hysteresis loops for total suspended solids (mg/L) and turbidity (ntu) as a function of discharge (cfs) in Hopland Watershed C from Feb. 21 to Feb. 24, 2001.

Linear regression analysis of TSS concentrations as a function of turbidity identified variability in relationships within and between the HREC and SFREC watersheds (figs. 6a, b). The correlation coefficients for the seven watershed TSS and turbidity regression analyses were all significant ($p < 0.001$). At HREC, with erosive soils derived from sedimentary parent material, turbidity measurements explained from 89 percent (HREC Watershed B) to 58 percent (HREC Watershed C) of the variability in TSS. At SFREC, with relatively more stable soils, turbidity explained 58 percent (SFREC Watershed 1) or less of the variability in TSS. Regression line slopes were significantly steeper at HREC than SFREC. Test for homogeneity of slopes indicates that the seven TSS and turbidity regression slopes are significantly different from each other ($p < 0.001$). Additional iterative tests for homogeneous slopes between the HREC and SFREC watershed regression lines found that all slopes were significantly different from each other (table 2).

Table 2—Test for homogeneity of regression line slopes within the four Hopland and three Sierra Foothill Research and Extension Center Experimental Watersheds.

Site	Watershed	Hopland				Sierra		
		A	B	C	D	1	2	3
Hopland	A	1	-	-	-	-	-	-
	B	<0.001	1	-	-	-	-	-
	C	0.003	<0.001	1	-	-	-	-
	D	<0.001	<0.001	0.035	1	-	-	-
Sierra	1	<0.001	<0.001	0.014	<0.001	1	-	-
	2	<0.001	<0.001	<0.001	<0.001	0.016	1	-
	3	<0.001	<0.001	0.008	0.011	<0.001	<0.001	1

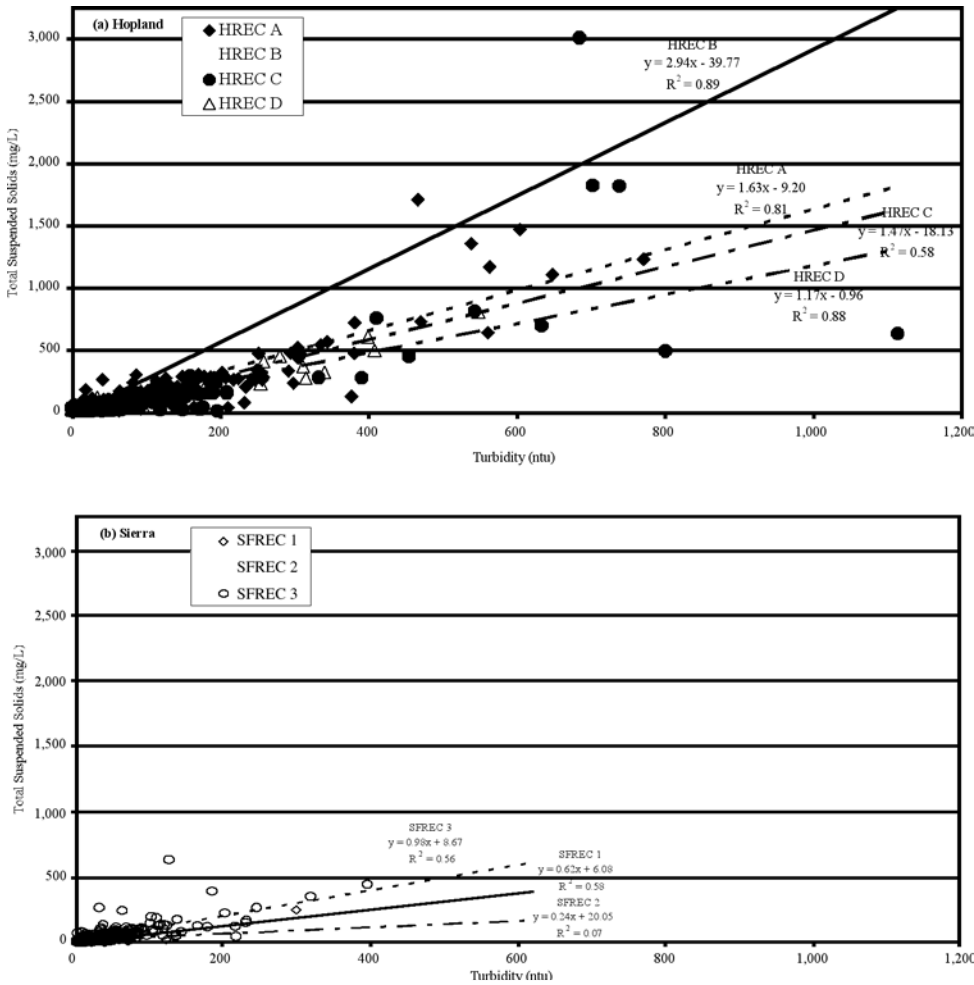


Figure 6—Total suspended solids (mg/L) as a function of turbidity (ntu) in (a) four oak woodland watersheds at Hopland and (b) three oak woodland watersheds at Sierra Foothill.

Discussion and Conclusions

When an indicator of water quality is utilized, such as turbidity, it is important to understand its benefits and its shortfalls. Turbidity is more cost effective than TSS and the relationship between TSS and turbidity is generally strong and well documented. However, it is also site specific. Similar turbidity values from two different tributary watersheds could indicate appreciably different TSS values. This is a result of differences in watershed geology, slope and aspect, soils, vegetation, and land use.

TSS concentrations and turbidity values in California's oak woodland watersheds are variable across seasons and storms and can be explained by the Mediterranean climate and intermittent hydrology of these watersheds. As streamflow rises and falls during storms, TSS concentration and turbidity increase and decrease, respectively. An additional aspect of the storm variability is the demonstrated hysteresis of TSS and turbidity values with regard to discharge, which has been observed in other coastal watersheds (Paustian and Beshchta 1979). The need to account for seasonal and storm variability in water quality monitoring programs has been investigated and discussed previously (Tate and others 1999). Those results combined with this study's results clearly indicate the need for intensive, storm-based sampling for adequate characterization of TSS and turbidity in oak woodland watersheds.

Mean TSS and turbidity within the HREC watersheds were significantly different, and in all but one case, greater than those observed in the SFREC watersheds. Regression slopes greater than one in the HREC watersheds indicated that a greater TSS concentration corresponds to a respective turbidity measurement in HREC watersheds than in SFREC watersheds (*figs. 6a, b*). On average, HREC receives ten more inches of annual precipitation than SFREC, contributing to differences in rainfall-to-runoff relationships between the two sites and, therein, TSS and turbidity. The soils and geology in the HREC watersheds are considered to be more erosive than those in the SFREC watersheds, contributing to this observed difference. It is also possible that this difference could result from the influence that particle size, sediment composition (organic versus inorganic particles), and water color have on turbidity measurements (Clifford and others 1995, Gippel 1995). Particle-size analysis and comparisons of the organic solid components within HREC and SFREC suspended solids could help in understanding the difference between the two sites.

Comparison of TSS and turbidity regression slopes within each set of experimental watersheds raises questions about the ability to extrapolate between watersheds previously considered to have similar climate, geology, soils, and hydrology. TSS versus turbidity relationships, specifically regression slopes, were significantly different for HREC and SFREC watersheds, (*table 2*). For example, a monitoring program applying the HREC Watershed D regression relationship of TSS and turbidity to HREC Watershed B would underestimate TSS concentrations by 1, 54, and 60 percent for turbidity measurements of 1, 100, and 1,000 ntu, respectively. In a case where the regression line for SFREC Watershed 3 was applied to Watershed 2, TSS concentrations would be overestimated by 52, 142, and 280 percent for turbidity measurements of 1, 100, and 1,000 ntu, respectively. As indicated in this comparison, error in TSS estimation will depend on the turbidity value because regression slopes are diverging as turbidity increases. The greatest error will occur during storms when the highest TSS concentrations and turbidity values are generated.

This has implications for intended efforts to monitor impacts and benefits from land-use management and watershed restoration on in-stream conditions, as well as environmental regulation based on TSS estimations from turbidity. Turbidity can be utilized as an effective and accurate indicator of TSS concentrations. Because the relationship of these two parameters is watershed specific, water quality monitoring efforts will need to take the time to establish the relationship for each watershed to be monitored. That relationship should be established with data collected across a full

range of streamflows to represent the seasonal and storm variability of TSS and turbidity demonstrated in California oak woodland watersheds.

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