TURBIDITY MEASUREMENTS FOR DETERMINATION OF SEDIMENT SOURCE AND RETENTION IN RIVER AND MARSH ENVIRONMENTS.

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INTRODUCTION

A key component of the conservation of water quality is the prevention of the introduction of excess suspended sediment (SS). Sediment is a major pollutant of U.S. waterways. (Nearly et al. 1989). In addition to impacting water clarity and quality for swimming and drinking purposes, sediment clogs spawning grounds and aquatic habitats. Agricultural practices, timber harvest and associated roads, are chief sources of suspended sediment. Water quality monitoring networks provide a means of identifying regions with high loading rates, comparing different land management practices and examining the roles of geomorphologic and hydrologic variables. This information can be used to guide management and permitting activities by identifying erosional “hot spots”: specific soils, slope positions, or landscapes that are unstable when disturbed; and specific harvesting, road placement or agricultural practices that result in high sediment loading. Sediment loading can be episodic, dynamic and highly variable. Thus monitoring need to be either triggered by storm events or running continuously. If the intent is to compare loading rates between different landscapes and management practices, it is important to compare storm events of similar magnitude and intensity- optimally, the same event. This creates a need for monitoring simultaneously at several locations to compare responses. Networks of *in situ* turbidometers can greatly increase the resolution and power of monitoring networks by providing continuous water quality data at multiple locations.

The measurement of turbidity as a surrogate for suspended sediment is dependent on the consistency of the relationship between the two over the full range of sediment loading conditions at a site. If the intent of the study is to determine particle size variations over time, laser diffraction instruments (Topping 2000) would be more appropriate. However if an adequate calibration between SS and turbidity can be obtained the method offers an inexpensive means of recording and integrating SS flux over a wide range of time scales and spatial comparisons.

Lake Tahoe has shown a steady and steep decline in clarity over several decades (Goldman 2000) making studies of sediment source and retention critical. This paper presents three examples of the use of turbidometry in the Tahoe basin. The first application was the creation of a sediment budgets for subalpine forested and rockland watersheds of the west shore of Lake Tahoe (Figure 1). We compared subwatersheds draining metasedimentary and volcanic regolith, and headwater and valley stream reaches. Turbidometry was useful for this application because the majority of sediment loading occurs during the spring snowmelt. Access to the upper watersheds is difficult at this time because of deep snowpacks and rugged terrain, and the discharge varies dramatically due to snowmelt fluctuations.

The second application was the measurement of the retention of SS within a freshwater marsh. Most monitoring stations are located upstream of river deltas to avoid tidal or backwater effects on discharge measurements. The result is very little information on sediment retention of deltas. In South Lake Tahoe, California, the Upper Truckee River and Trout Creek come together in the Truckee Marsh before emptying into Lake Tahoe (Figure 2). Previous monitoring on both rivers had largely taken place above the marsh. Formerly one of the largest wetlands in the Sierra Nevada, the marsh has been extensively modified, with a marina and a housing development placed in the center. A canal was excavated to make the Upper Truckee River bypass the developed area. We installed turbidity monitors above and below the wetland portion of each river as a means of comparing sediment retention within the unimpacted and channelized rivers.

The third application was the detection of hysteresis, the variation in the relationship between SS and discharge over daily and seasonal time periods. By continually measuring SS and discharge, it was possible to observe flushing and sediment exhaustion, phenomenon that are important for understanding in channel storage of sediment, potential rates of recovery, and design optimal sampling protocols.

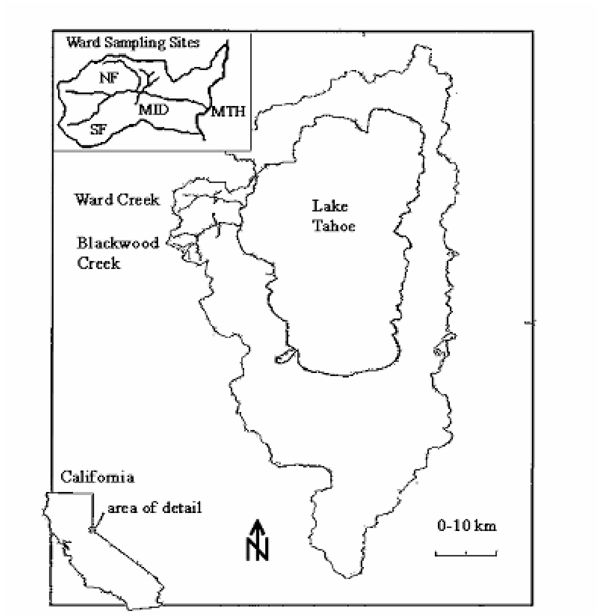

Figure 1 Ward Creek at Lake Tahoe. Inset: sampling locations.

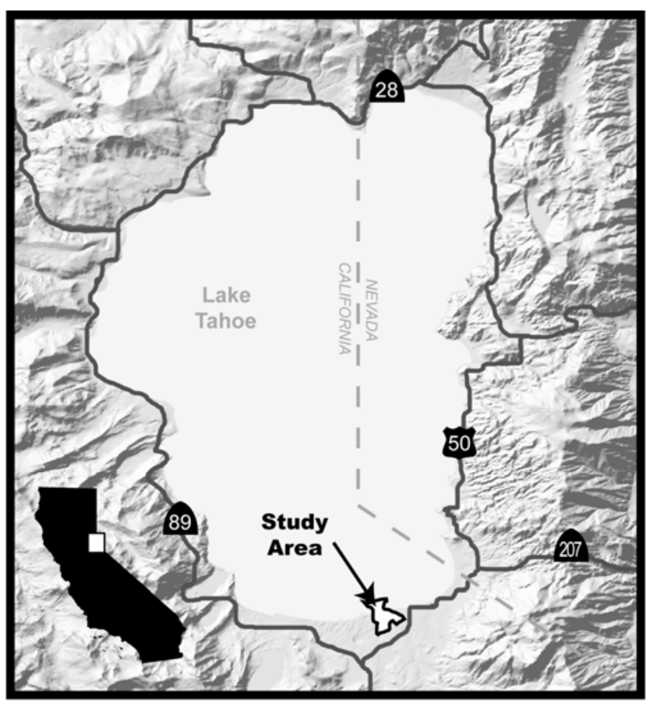

Figure 2 Truckee Marsh at South Lake Tahoe, CA. (Figure 2, 4; Table 2, 3 © Springer Science and Business Media, Stubblefield et al. 2005a).

METHODS

Ward Creek (25 km^2) extends from 1900 m at lake level to 2700 m at the watershed boundary. It is predominantly forested with conifers, with urban development at the lake shore and subalpine zones above treeline. The North Fork is predominantly regolith derived from metasedimentary rocks. The South Fork has volcanic and granitic outcrops, with its most notable feature a large mudflow breccia badlands. The main stem has a lower steep walled canyon section with cobble sized alluvium and occasional exposed bedrock. The upper section of the main stem opens into a broader valley with pebble-sized alluvium.

Sediment budgets are quantitative measurements of inputs, outputs and storage within a designated region. To create a sediment budget for Ward Creek on the west shore of Lake Tahoe we focused on quantifying SS loads entering and exiting river reaches. We installed a network of four turbidometers to quantify sediment loading in the South and North Forks of the watershed, and the upper and lower reaches of the watershed (inset, Figure 1). Data was collected for the spring snowmelt seasons of 1999, 2000, and 2001. Long term monitoring of Tahoe watersheds (Rowe 2002) indicate that the bulk of SS is transported during spring snowmelt. Optical backscatter nephelometers were connected to dataloggers. Twelve readings were made per minute, and the average stored every fifteen minutes. Grab samples of river water were taken weekly, and during peak flows. Samples were analyzed gravimetrically for TSS and compared to concurrent turbidity readings for calibration. Continuous discharge measurements were available from USGS monitoring stations at three locations within the watershed. Discharge in the North and South Forks were determined using standard gauging techniques and related to USGS station data from just below the confluence. Turbidity data was converted to SS concentration using the calibration data. SS concentration per 15 minute time step was then multiplied by flow volumes and summed over longer time periods to generate sediment loads at each site. Further details are provided by Stubblefield (2002).

The Truckee Marsh is approximately 400 ha. A barrier beach lies between the marsh and the lake. Vegetation is primarily grass and sedge, with some regions of willow and conifer. In 2003, the year of this study, the Trout Creek divided into two distributaries, one passing through a lagoon, and the other a beaver dam, before rejoining each other, and exiting into Lake Tahoe. The Upper Truckee River meanders through the upper marsh before reaching the straight canal reach and exiting into Lake Tahoe. The Trout Creek watershed has an area of 10,674 ha. The Upper Truckee Watershed has an area of 14,673 ha. Both rivers have sandy alluvium in the lower reaches.

For the measurement of SS retention on the Upper Truckee Marsh, turbidometers, and velocity and stage recorders were installed above and below the marsh reaches of the Trout and Upper Truckee rivers. Instrumentation was also installed at a mid-marsh station in Trout Creek. Sampling was focused on the spring snowmelt as this represents the bulk of sediment loading for subalpine Sierra watersheds. SS samples were collected with depth-integrated flow samplers. Sediment loads entering and exiting the marsh were compiled as described above for Ward Creek. Further description is provided by Stubblefield et al. (2005a).

In addition to creating a sediment budget from the Ward Creek data, we examined sediment transport dynamics. For specific flow events, we plotted the ratio of concentration at 15 minute intervals (C) as a fraction of peak concentration (Co) versus discharge at 15 minute interval (Q) as a fraction of peak discharge (Qo). The resulting graphs (C/Co versus Q/Qo) highlight changes in the relationship of SS and discharge over time. We also compared sediment yields estimated from turbidometry with estimates generated from a sediment rating curve method. Further description is provided in Stubblefield et al. (2005b).

RESULTS

Excellent correlations were found between suspended sediment and turbidity values for four Lake Tahoe basin tributaries: Ward Creek (1999-2001, r^2 =.95), Blackwood Creek (2001, r^2 =.91), Upper Truckee River and Trout Creek (2003, combined r^2 =.90). Turbidity and discharge data for Ward Creek in 1999 is shown in Figure 3. Turbidity fluctuations are closely linked to daily discharge peaks from snowmelt. Turbidity responses tend to be sharper peaks, occurring on the rising limb of the hydrograph, and falling faster than the discharge falling limb. Turbidity response to discharge appears to lessen over the course of the season. For example, the turbidity response on May 13 is much greater than June 13, 1999 for roughly

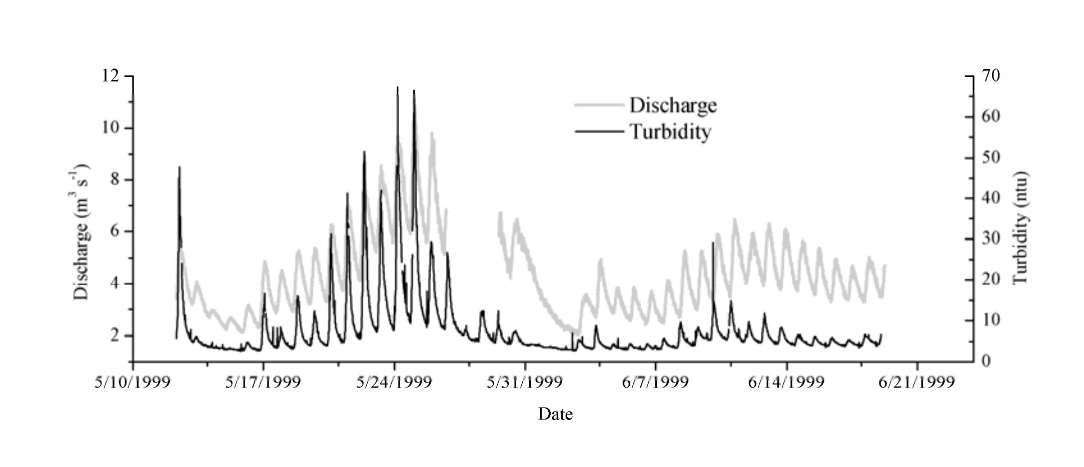

Figure 3 Turbidity and discharge. Ward Creek, 1999. (Figures 3, 5, 6 © John Wiley & Sons Ltd., Stubblefield et al. 2005).

equivalent discharge levels (Figure 3). Sediment budgets for 1999, 2000 and 2001, created from the SS turbidity regression, and the turbidity and discharge record for each site, are shown in Table 1a. Because of sensor blockages and electronic malfunction, the budgets are constructed for time periods in which all four sensors were operational, 6 days in 1999, 34 days in 2000 and 29 days in 2001. The short record of 1999 occurred during peak flow, when the bulk of SS was transported. Budgets indicate high specific sediment loads for the South Fork, and the Upper Main Stem of Ward Creek. A closer look at 3 distinct pulses in the snowmelt load for 2000 is shown in Table 1b. At different times within the season, the Lower Main Stem goes from storing sediment (negative values) to releasing sediment. The South Fork makes steady contributions, and the Upper Main Stem with a high initial load, drops steadily as the season progresses.

Table 1 Ward Creek sediment budget (kg/ha/d).

a. Specific Sediment Loads for 3 years (kg/ha/d)

Basin	1999	2000	2001*
North Fork	4.2	1.1	0.6
South Fork	7.1	3.0	
Upper Main Stem	19.6	2.4	0.1
Lower Main Stem	4.7	2.4	0.2
Duration (d)	6	34	29

* Single headwater station for 2001 below confluence.

b. Sediment Loads for 3 Events in Snowmelt 2000 (kg/ha/d)

	Event#			
Basin	1	2	3	Total
North Fork	0.1	2.0	0.6	1.1
South Fork	2.1	4.4	2.17	3.0
Upper Main Stem	8.6	3.9	0.73	2.4
Lower Main Stem	-4.6	7.8	-0.1	2.4
Duration (d)	2.3	12	20	34

Table 2 Trout Creek suspended sediment (SS) load.

	Time Period*	Above Marsh	Mid Marsh	Below Marsh	Retention
Discharge (m^3)	1	11,524,793	5,384,165	n/a	
	2	953,798	550,062	785,031	18%
	3	643,131	293,324	424,457	34%
SS Total Load (Mt)	1	260	89	n/a	
	2	39	18	12.5	68%
	3	33	10	3.4	90%
SS Load per Unit Volume (Mt/m^3)	1	2.3(-5)	1.7(-5)	n/a	
	2	4.1(-5)	3.3(-5)	1.6(-5)	
	3	5.1(-5)	3.4(-5)	8.0 (-6)	

*Sample period 1 was May 6 to June 17. Sample periods 2 and 3 are subsets of 1. They are May 21 to May 25, and May 27 to May 29 respectively.

Data for sediment retention for the spring snowmelt 2003 are shown for Trout Creek in Table 2 and the Upper Truckee River in Table 3. Retention of SS was 26% on average for the Upper Truckee River, with a daily range of 13-41%. Retention of SS was much higher for Trout Creek, ranging from 68-90%. The Trout Creek retention estimate was based on the peak flow period. Data from Mid and Above Marsh stations indicate similar retention trends for longer time periods. Discharge results indicate higher retention of water within the Trout Creek portion of the marsh, with 18-34% retention as compared to the Upper Truckee River with 6% retention. The Mid Marsh discharge values for Trout Creek are lower than the Mouth because a side channel, ungaged in this study, carried more flow than was predicted in designing the experiment. For this reason a measure of concentration, SS Load per Unit Volume, is presented in Table 2. It indicates that there was a reduction in SS concentration between the Above and Mid stations, but not as large as might be suggested by the Total Load results. Examining the SS Load per Unit Volume results, it is apparent that the greatest reduction in SS concentrations took place in the lowest reach of the marsh, between the Mid and Below stations. Turbidity data is supported by grab sampling results shown in Figure 4. SS concentrations at the two Mouth stations were consistently low, regardless of incoming SS concentrations measured at the Above and Mid stations.

Table 3 Upper Truckee River suspended sediment (SS) retention.

	Time Period*	Above Marsh	Below Marsh	Retention
Discharge (m^3)	Total	7,090,095	6,636,520	6%
SS Load (Mg)	May 12 - 14	14	8	41%
	May 15 - 16	6	5	24%
	May 16 - 17	24	21	13%
	May 17 - 22	177	130	26%
	May 28 - 28	20	15	26%
	May 29 - 29	22	15	32%
	Total	263	194	26%

A continuous record makes it possible to examine variations in the relationship between SS and discharge. Figure 5 is a hysteresis graph for a rain on snow event occurring on May 10, 2000 at the Mouth station of Ward Creek. During the rising limb the SS concentration rises quickly, achieving peak concentration at 80% of peak flow. The fall of SS is more precipitous, with concentrations at 40% of peak, while flow has only returned to 80% of peak level. Hysteresis is also observed at the seasonal level as described above for

Figure 4. As an evaluation of the effects of hysteresis on sediment load estimates, turbidity based daily loads were plotted against sediment rating curve loads for Ward Creek. Total SS load from the turbidity estimate was 80.2%, 98.5%, and 58.4% of rating curve estimates for the years 1999, 2000, 2001, respectively. The data for 1999 is shown in Figure 6 and inset. Rating curve estimates appear to underestimate turbidity loads during peak flow and overestimate loads during low flow periods.

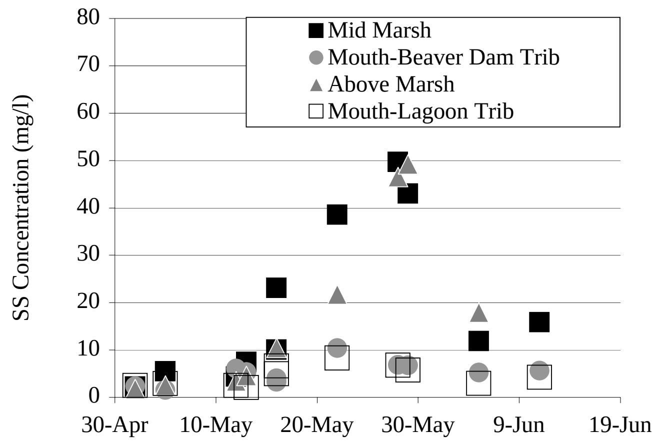

Figure 4 Trout Creek SS concentrations from grab-sampling, 2003.

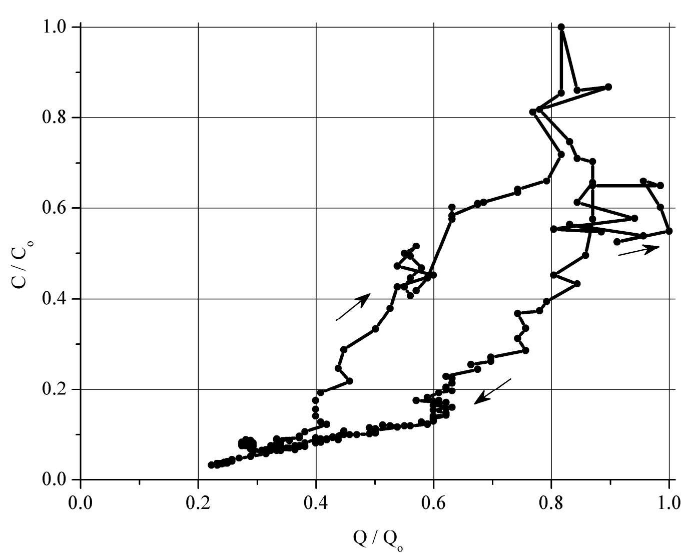

Figure 5 Hysteresis plot for Ward Creek, May 10, 2000.

DISCUSSION

The results presented here demonstrate the efficacy of turbidometry for determining sediment source and sediment retention characteristics for SS concentrations of 1-100 mg/l. The high-resolution data set generated by turbidometric measurements indicates sediment delivery dynamics with important implications for monitoring networks and rates of stream recovery.

The high SS loads from the South Fork of Ward Creek are likely the result of the badlands region. Within the subcatchment, other erosion sources are unlikely. Forested regions typically have low sediment outputs (ref). Visual inspection of the channel course indicates very little bank erosion. Other indications of high rates of erosion are pedestalled trees, with a 20 cm gap between the root crown and the current land surface, exposed bedrock surfaces without rock varnish, highly friable and unconsolidated regolith, and extensive

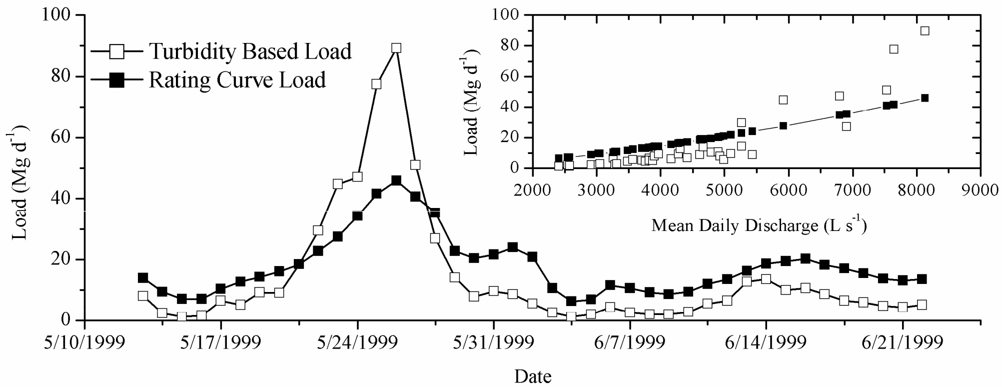

Figure 6 Comparison of turbidity and sediment rating curve-based load estimates. Ward Creek, 1999.

networks of rills and gullies. The Tahoe basin was heavily overgrazed by cattle and sheep (Holland 1987). It is possible the badlands were initiated by overgrazing. Cold thermal conditions and limited moisture in montane climates can limit revegetation of badland surfaces (Regues et al. 2000).

The Upper Main Stem also had high SS loads. A landslide on the south slope reached the stream course during a hundred year flood event in 1997. However during the average flows recorded during 1999-2001 (see Stubblefield, 2002) the landslide did not appear to contribute to SS loads. A few gravel tongues extended down to the channel, with no fines evident. Inspection of the channel course showed limited bank erosion. However it is difficult to visually assess the impact of bank erosion since a small increment over many kilometers of river can be significant. The other source of fines, suggested by inspection of the Upper Main Stem, is mud drapes deposited by summer and fall thunderstorms (Dunkerly and Brown 1999). During a high intensity rain event observed by the authors, large quantities of SS were washed into the channel. The sediment was traced to the badlands region of the South Fork. Thunderstorms typically occur during summer low flow periods, when sediment transport capacity may not be sufficient to transport it to the lake. The material remains as a coating on sands and gravels and in interstitial spaces. The decrease in specific sediment loads in the Upper Main Stem during 2000 (Table 1b) may represent the gradual winnowing of instream fine sediment deposits deposited during earlier events.

The sediment retention characteristics of the Truckee Marsh reflect floodplain connectivity. The Upper Truckee River is highly incised, with two meter high banks preventing movement of snowmelt flows out into the marsh. Constrained flows result in the reach acting like a pipe, directly transmitting SS with little retention. High rates of bank erosion can result in sediment yield rather than retention. Conversely in the Trout Creek section of the marsh, particularly the lower reach, flows spread out over a wide area. During late May, 2003, snowmelt waters moved out over much of the 80 area. Resulting low flow velocities and increased contact with the bottom sediments result in greater sediment retention. Channels are small, and stabilized by vegetation. By diverting flows to the north, the barrier beach creates a lagoon, backing up water and increasing marsh flooding. As the Upper Truckee River is the largest source of SS in the Tahoe basin, the results of this study indicate that restoration of floodplain connectivity has the potential to greatly reduce SS loading to Lake Tahoe.

Clockwise hysteresis is an indication of sediment exhaustion (Asselman 1999). It was observed in single events (Figure 5) and over the course of the snowmelt season (Figure 3). Hysteresis has two implications.

The first is that sediment rating curves dependent on a stationary relationship between SS and discharge may be subject to bias. Coats suggested that reduced grab sampling frequency during the falling limb of the seasonal hydrograph would result in a sediment rating curve that overestimated sediment loading (2002). Figure 6 gives an example of this bias, with rating curves overestimating during low flow and underestimating during peak flow events. The second implication of sediment exhaustion is the existence of a condition of limited sediment supply in relation to transport capacity. If loads from the upper watersheds and banks were reduced, Ward Creek would return to excellent water quality levels in a short time period.

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