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Retention of suspended sediment and phosphorus on a freshwater delta, South Lake Tahoe, California

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Abstract

The Upper Truckee River and Trout Creek, two major tributaries inflowing to Lake Tahoe, join to form what was historically the largest wetland in the Sierra Nevada mountain range that separates California and Nevada (USA). In the 1950s the delta floodplain of the Upper Truckee River was greatly reduced in area (38%) by urban development and the diversion of the river into a single excavated channel. Conversely, Trout Creek still flows through a wide marsh system with significant overbank flooding before entering Lake Tahoe. This study hypothesized that river channel reaches that are not incised within the delta floodplain retain more sediment and nutrients as a result of greater floodplain connectivity, compared to more incised and excavated reaches. Suspended sediment (SS) and total phosphorus (TP) load data from the delta formed by the Upper Truckee River and Trout Creek were collected using flow stage sensors, turbidometers and depth-integrated samples. During the spring snowmelt flow events monitored in 2003, SS load was reduced by 13–41% for the Upper Truckee River and by 68–90% for Trout Creek. Similar reductions in TP load were observed: 13–32% for the Upper Truckee River and 61–84% for Trout Creek. Monitoring of Trout Creek indicated a reduction in load per unit volume of 20–34% in a moderately incised reach versus a reduction of 51–77% in a non-incised marsh reach containing lagoons, braided channels and backwater areas created by a beaver dam. Smaller particle sizes, $< 10\ \mu$m, were retained in the lower marsh reach with similar efficiencies as larger particle sizes. If retention rates from the Trout Creek portion of the marsh are applied to the Upper Truckee River, sediment loading to Lake Tahoe for 2003 would have been reduced by 917 tons of SS.

Introduction

Elevated concentrations of sediment and nutrients resulting from agricultural activities, urbanization, and other land uses have deleterious impacts on aquatic systems, impacting benthic organisms (Mebane 2001), spawning gravel habitat (Chapman 1988), and water clarity and quality (Wetzel 1983). Natural and constructed wetlands reduce deleterious impacts through the trapping of particulates into sediment and peat layers and the assimilation of nutrients from inflowing waters into plant and microbial biomass (Kadlec and Knight 1996; Kennedy and Mayer 2002). However, the assimilative capacity of wetlands is finite (Richardson et al. 1997; Kadlec 1999) and varies significantly between wetlands, depending on soil and vegetation characteristics (Mitsch 1977), hydrologic regime (Fennessy and Mitsch 2001), and input concentrations (Richardson et al. 1997). Current research efforts seek to understand the processes by which wetlands remove sediment and nutrients from agricultural and urban runoff in order to inform efforts to conserve natural wetlands, to restore impacted wetlands, and to design constructed wetlands maximizing long-term removal efficiencies.

This study provides a quantification of sediment and nutrient retention for the floodplain of a fluvial and wave-dominated freshwater lacustrine delta. Recent attempts to estimate global sediment delivery to the world's oceans has highlighted the importance of research in delta depositional systems (Syvitski et al. 2005). Current monitoring efforts are often upstream of deltas, and sediment retention within the delta floodplain, front and prodelta can be quite high. Deltas are progradational deposits formed at the terminus of river systems. As the confined flow of the river channel expands and slows down, sediment is deposited on the emergent delta floodplain and subaqueously on the delta slope and prodelta (McLane 1995). In the case of fluvial-dominated deltas, mid-channel mouth bars result in repeatedly bifurcating distributary channels. Waves rework mouth bar deposits into shore parallel beach ridges and barrier islands. Wave and fluvial factors combine to form lobate floodplains located behind beach ridges. The resulting landscape has depositional environments similar to river floodplains including distributary channels, levees, splays, backwater lagoons and marshes. Primary differences from a riverine wetland result from the high density of distributary channels, and the low gradient, approaching the ponded condition of lake level.

Retention of sediment and associated nutrients is of particular concern at Lake Tahoe, California-Nevada. In recent decades, the increasing population and expansion of tourism has been accompanied by a steady decline in water clarity, an increase and shift to phosphorus-limitation of primary productivity, and an increase in attached algae around the perimeter of the lake (Goldman 1988). Time series analysis of long-term water quality data indicates the importance of reducing watershed sources of suspended sediment and phosphorus to slow the decline of water quality (Jassby et al. 1994, 1999). The watershed chosen for this study has been identified as having high sediment and phosphorus loads in comparison to other Lake Tahoe Basin rivers (Rowe et al. 2002).

Suspended sediment (SS) and total phosphorus (TP) retention were quantified for reaches of two rivers with contrasting geomorphology and floodplain connectivity, using grab sampling and continuous turbidometry. Properly calibrated turbidometry data can greatly improve measurement of SS loading dynamics (Bunt et al. 1999), as compared to grab sampling alone. The Upper Truckee River has a highly incised channel and low floodplain connectivity, while Trout Creek has a minimally incised channel and high floodplain connectivity, especially in the lowest reach. Overbank flows provide an important pathway for the transport of water, sediment, and inorganic nutrients to the floodplain and organic carbon to the channel (Junk et al. 1989; Tockner et al. 2000). Reductions in overbank flow timing, frequency, and duration can fundamentally alter nutrient cycling pathways, processes, and rates (Heiler et al. 1995). Therefore, we hypothesized that SS and TP retention would be higher on Trout Creek. The results of this study present a quantification of the effects of low and high floodplain connectivity on SS and TP load exiting freshwater marsh ecosystems.

Site description

The study site is a delta floodplain formed where the Upper Truckee River and Trout Creek discharge to Lake Tahoe at South Lake Tahoe, California (Figure 1). Lake Tahoe was formed by graben faulting approximately 3 million years ago (Hyne et al. 1972), while landforms of the Upper Truckee River and Trout Creek were principally shaped from tectonic and glacial processes (Hyne et al. 1972). Lake Tahoe is the eighth deepest freshwater lake in the world, and is world-renowned for its water quality (Goldman 2000). Several factors explain the exceptional clarity of Lake Tahoe. It has a large volume (156 km^3), low sediment inputs from a

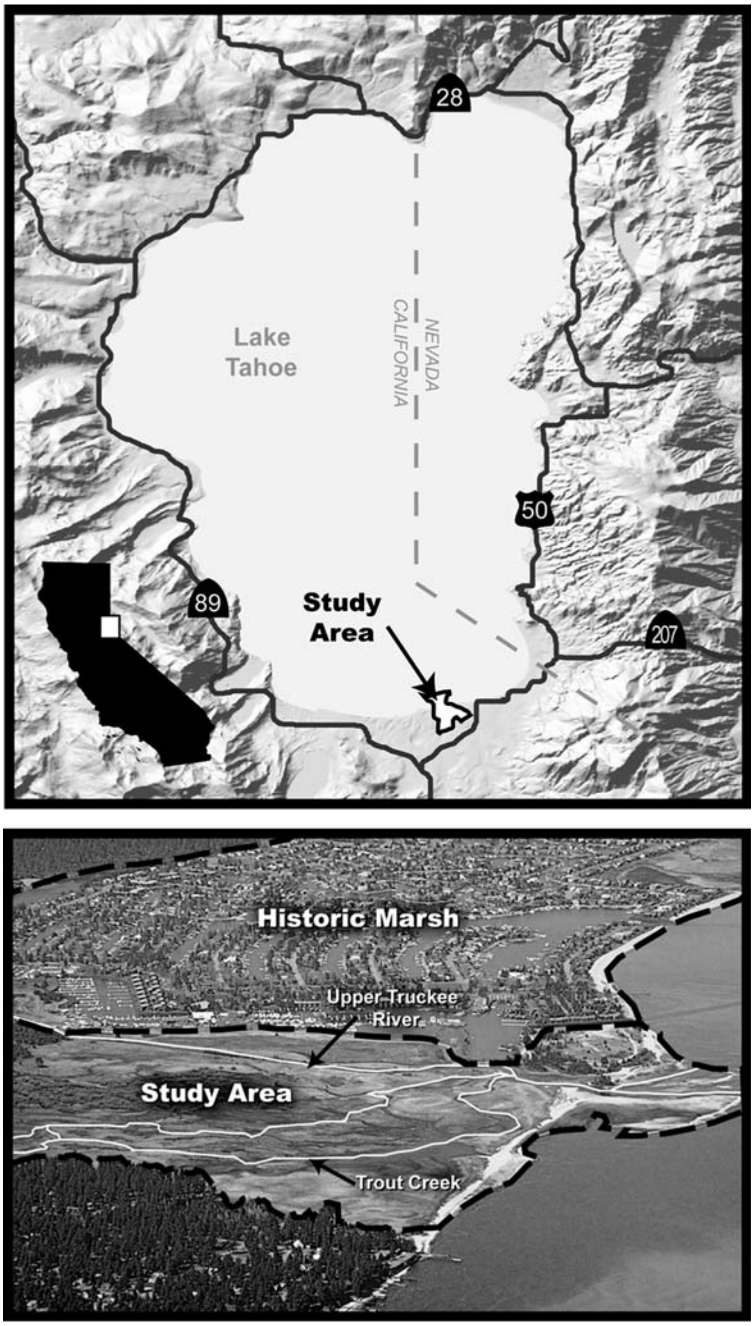

Figure 1. Lake Tahoe and study site location. The top map indicates the location of Lake Tahoe within California and Nevada and the location of the study site within the Lake Tahoe watershed. The bottom photograph indicates the location of the Upper Truckee River and Trout Creek within the remaining marsh, and the extent of development of the historic marsh. The perspective is from the east. Adapted from map created by EDAW, Inc.

forested and largely granitic watershed (800 km^2), and a small watershed to lake surface ratio (1.6) (Jassby et al. 1999).

The Upper Truckee River and Trout Creek drainage basins represent 31% of the total watershed area draining into Lake Tahoe (Table 1).

Table 1. Characteristics of watersheds, including drainage area, length, width, depth, cross sectional area, and representative flows for 1961–2001 (Patterson et al. 2003, and Rowe and Allander 2000).

	Upper Truckee River	Trout Creek
Drainage area (ha)	14,673	10,674
% Total drainage Lake Tahoe	18	13
Marsh area (ha)	320	80
Length (km)	34	24
Width (m)	17.3 ± 4.79	7.9 ± 2.26
Depth (m)	1.7 ± 0.32	1.1 ± 0.30
Cross-section area (m^2)	19.2 ± 5.02	6.3 ± 2.83
Snow-melt flow (m^3/s)	5.4–14.2	1.4–4.2
Bankfull flow (m^3/s)	29.4–44.2	4.2–5.6

Mean and standard deviation of width, depth, and cross-section area for cross sections (UTR: $n = 16$, TC: $n = 6$) located at incremental distances downstream of Hw50 on the main single thread channel of both rivers.

The Upper Truckee watershed is the largest and most heavily urbanized watershed in the Lake Tahoe basin (Hatch et al. 2001). A major impact on the Upper Truckee River watershed was the construction of a housing development in the 1950s (C. Goldman, personal communication). Placed in the center of what was previously the largest wetland in the Sierra Nevada mountain range of eastern California, the development involved massive dredging and fill operations, the creation of a marina with a system of canals, the construction of homes, and the displacement of the Upper Truckee River from a system of distributary channels to a single straight ditch extending 800 m to the lake (Figure 1). The marshland area was reduced from 600 ha to 400 ha and divided into two peripheral marshes. In contrast with the Upper Truckee River, the adjacent Trout Creek watershed has seen fewer disturbances, partly because the U.S. Forest Service manages much of the watershed. Evidence of limited channel diversions conducted for ranching operations or utility installations are apparent on the delta.

The study site extends from the intersection of each river with Highway 50 to the junction of the two rivers at the shoreline of Lake Tahoe (Figure 2). In this area, both rivers travel approximately 3 km through the marsh system in the delta floodplain. The Upper Truckee River flows through an incised channel, while Trout Creek flows through a moderately incised channel with a side channel to the west, and, during the study period, through two small distributary channels further downstream (Figure 2). One distributary channel flowed through a ponded area created by a beaver dam before joining the Upper Truckee River. The other distributary channel divides into smaller channels that flow into a lagoon backwater behind a barrier beach before draining west to join the Upper Truckee River. The moderately incised reach of Trout Creek is designated ‘Upper Reach’, while the distributary reach of Trout Creek is designated ‘Marsh Reach’. Because of the geomorphological differences between the Upper and Marsh Reaches, two reaches were monitored on Trout Creek, as opposed to one on the Upper Truckee River.

Geomorphic and hydrologic parameters for the two rivers are listed in Table 1. UTR basin stretches out from north to south while TC is fan-shaped with an east to west course. Both basins extend through the same geologic substrate dominated by granitic rock with similar soil type, glacial deposits, and lacustrine sediment. Both UTR and TC are very low gradient, predominantly coarse sand bed, alluvial streams with average bed gradients of about 0.002. The two watersheds have similar elevations and drainage areas. However, as a result of different basin morphology, rainfall spatial distribution, snow pack accumulation, and runoff routing patterns, differences in channel dimensions and surface–groundwater interactions are observed between the watersheds. For instance, widths and snowmelt flows of Trout Creek are only about 30% of the Upper Truckee River, and Trout Creek stream flows are more perennial than those in the Upper Truckee River (Rowe and Allander 2000).

Methods

Field measurements

Discharge, SS concentration, and TP were measured upstream and downstream of each of the three study reaches within the delta floodplain region. Sampling was conducted during peak discharge events throughout spring snowmelt. For 2003 these events occurred on May 2, 5, 12–13, 16, 22–23, 28–29, and June 3, 5, and 11.

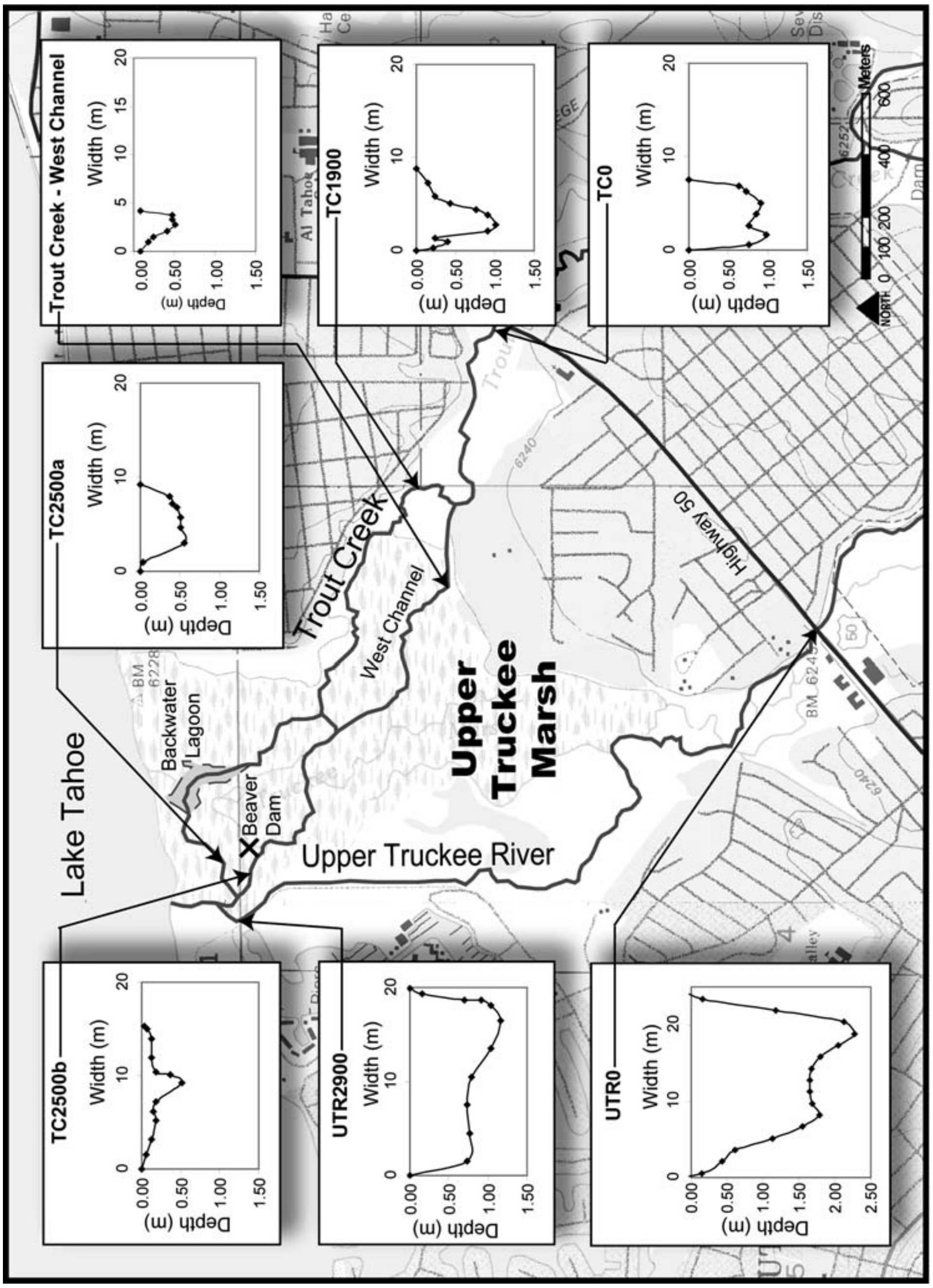

Figure 2. Study site at Upper Truckee River (UTR) and Trout Creek (TC). Figure indicates location of stations and reaches. Cross sections of the stations including floodplain from left to right, top row: TC2500b, TC2500a, middle row: UTR2900, TC1900, and bottom row: UTR0, TC0.

Long-term monitoring at Lake Tahoe has indicated that the bulk of annual sediment and nutrient loading occurs during the spring snowmelt (Hatch et al. 2001). For example, during Water Years 1991–1996, a mix of wet and dry years, 82% (±9% Standard deviation) of yearly SS loading on the Upper Truckee River and 62% (±12) on Trout Creek was delivered in the spring snowmelt months of March–June (Rowe et al. 2002).

Stations were named with numbers representing the distance in meters downstream from Highway 50 (e.g., UTR0 and TC0 are the stations at Highway 50 for the Upper Truckee River and Trout Creek, respectively). Sampling on the Upper Truckee River was conducted on one reach with two stations, while Trout Creek was divided into two reaches with a total of three stations (Table 2) (Figure 2). Data from two stations on Trout Creek, TC2500a and TC2500b, were combined later in the results. Differences between input and output loads were calculated to determine within-reach retention.

Discharge was measured at all five sites on weekly intervals using hand-held flowmeters positioned at 4/10ths of the depth from the bed and at a minimum of ten locations across a cross section. Stage–discharge rating curves were developed for each site to provide a continuous record of discharge.

Continuous discharge records were generated from available data as follows. Continuous stage data for the upstream sites, UTR0 and TC0, were obtained from the U.S. Geological Survey (USGS) stage gauges at the Upper Truckee Bridge (USGS station 10336610) and the Trout Creek Bridge (USGS station 10336790). For site UTR0 and TC0 the USGS rating curves were used to determine discharge from the USGS stage data. For sites TC 1900 and UTR2900, rating curves were developed for the discharge measured at the site and the USGS stage record from the respective upstream station. At site TC2500a, continuous stage data were obtained from a pressure transducer installed at the site. Discharge measured at the site was used with the stage data to generate continuous discharge data.

Continuous turbidity data for all upstream and downstream sites were obtained from *in-situ* optical backscatter turbidometers (OBS-3, D&A Instruments, Port Townshend, WA). The outflow of the TC Marsh Reach (Figure 2) consists of two distributary channels. A turbidometer was mounted in one of the channels (TC2500a). For the other channel (TC2500b) we assumed that if grab sampling of both channels showed little difference in concentrations, the turbidity record of the first could be used for both. Turbidometers were mounted with 5 cm PVC tubing oriented parallel to the current. The tubing was anchored with a T-joint to a steel rod pounded into the creek bed. Cables from the instruments were routed to dataloggers (CR-510, Campbell Scientific, Logan, UT) and power supplies located in weatherproof housings on the stream banks. Weekly maintenance of the turbidometers included cleaning the sensor surface, downloading data, and verifying sensor response. Turbidometer drift is estimated by the manufacturer to be less than 2% per year. Measurements were taken every second then logged as 15-min averages. Data were screened to delete erroneous values resulting from sensor obstructions. In these cases, linear interpolation was used to restore a continuous record for the estimate of total loading.

In addition to the continuous turbidity data, depth-integrated samples of water in the water column were collected on weekly intervals and analyzed for SSC and TP. Data were used to build correlations between turbidity and SSC and between turbidity and TP. SSC samples were collected at each site with a USGS DH-48 SS sampler, using the equal width interval method (e.g., Ward and Harr 1990). The volume of the

Table 2. Location of sampling stations.

River	Reach	Station[a]	USGS station[b]	Lat.	Long.
Upper Truckee River (UTR)		UTR0 below the intersection of Highway 50 and UTR	10336610	38°55.22	119°59.25
		UTR2900 mouth of UTR above the confluence with TC	–	38°56.32	119°59.42
Trout Creek (TC)	Upper reach	TC0 below the intersection of Highway 50 and TC	10336790	38°55.56	119°58.42
		TC1900 mid station between incised and marsh reaches of TC.	–	38°56.15	119°59.43
	Marsh reach	River divides into two distributary channels	–	38°56.15	119°59.43
		TC2500a terminus of TC distributary – lagoon branch	–	38°56.28	119°59.44
		TC2500b terminus of TC distributary – beaver dam branch	–		

[a] Station number indicates meters downstream from Highway 50.

[b] Associated USGS stations, latitude, and longitude, indicated for UT0 and TC0.

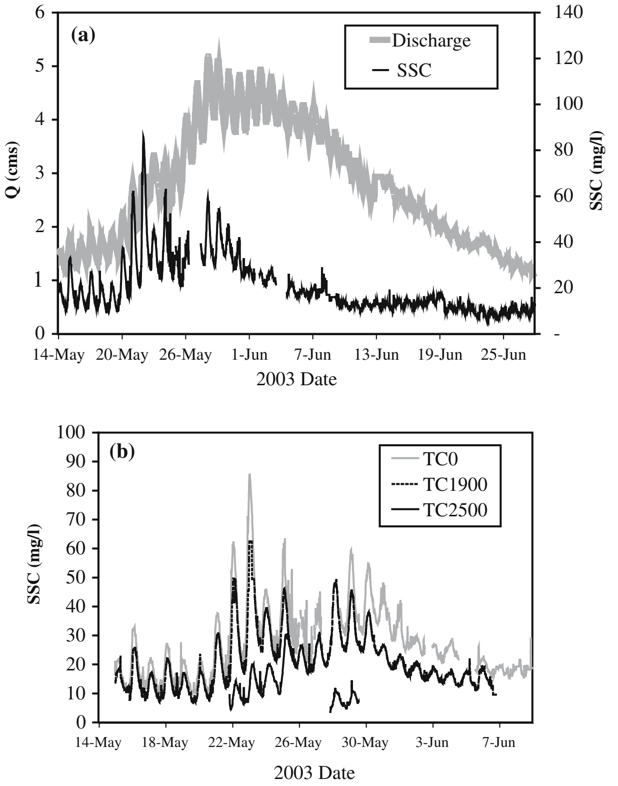

Figure 3. Hydrograph and suspended sediment concentrations for Trout Creek. Suspended sediment concentration as derived from turbidometry. SSC and discharge for TC0 are shown in the top panel (a) and the SSC record for TC0, TC1900, and TC2500 for the principal snowmelt period is shown in the bottom panel (b). The site names indicate meters downstream of the Highway 50 bridge over Trout Creek.

depth-integrated sediment samples varied from 800 to 2000 ml depending on discharge. SSC was determined by the gravimetric method (e.g., Ward and Harr 1990). TP was determined by the acid persulfate digestion/color spectrometric method (APHA 1990). Water samples also were analyzed for particle size distribution using a laser diffraction particle size analyzer (LS-320, Beckman Coulter, Inc., Miami, FL). To determine the proportion of different particle size classes, percentile distributions generated by the particle size analyzer were multiplied by the SSC results to yield mass concentrations for the size classes <1000 μm, <10 μm, and <1 μm.

SS and TP loads were calculated from discharge and SSC or TP data using Equations (1–5), below. For SS loads,

$$L_i = Q_i \cdot SSC_i \cdot \Delta t \cdot 60/10^\wedge 6 \quad [\mathrm{Mg}] \tag{1}$$

$$L_t = \Sigma L_i \quad [\mathrm{Mg}] \tag{2}$$

$$V_i = Q_i \cdot \Delta t \cdot 60 \quad [\mathrm{m}^3] \tag{3}$$

$$V_t = \Sigma V_i \quad [\mathrm{m}^3] \tag{4}$$

$$\mathrm{LC} = L_t / V_t \quad [\mathrm{Mg/m}^3] \tag{5}$$

where L_i is the suspended sediment load for time interval i, L_t is the total suspended sediment load or summation of L_i for the sampling period, V_i is the water volume for time interval i, V_t is the summation (volume) of V_i for the sampling period, Q_i is the average discharge during time interval i in m^3/s units, SSC_i is the average suspended sediment concentration during time interval i in mg/l units, Δt is the 15-min sampling interval (in minutes), 60/

10^6 is the conversion factor to get megagrams (Mg) units in Equation (1), 60 is the conversion factor to get m^3 units in Equation (3), and LC is the suspended sediment concentration for the sampling period. For TP loads, the same equations are used with TP_i replacing SSC_i in Equation (1) and L_i, L_t, and LC being phosphorus load for time interval *i*, TP load , and TP concentration for the sampling period, respectively.

Results

The 2003 snowmelt period began in the first week of May and ended in the first week of June (Figure 3). The snowmelt peak occurred in the last week of May. Depth integrated samples were taken at all monitoring sites on twelve dates during the Spring 2003 snowmelt period. SSC and TP values from these samples are shown in Figure 4a–d. Concentration values indicated significantly lower magnitudes of SSC leaving Trout Creek (stations TC2500a and TC2500b), than entering (TC0 and TC1900) (Figure 4b). SSC did not change appreciably between Upper Truckee River stations upstream and downstream (Figure 4a). The correlations between turbidity and both water quality variables (SSC and TP) had regression coefficients of 0.90–0.95. On the basis of these regressions, continuous turbidity was converted to continuous SSC and TP.

For Trout Creek stations TC0 and TC1900, discharge was calculated from the correlation between upstream USGS gauging station depths and discharge measured at each site with flowmeters. Discharge for sites TC2500a and TC2500b was determined by developing a stage-rating curve with a pressure transducer located in the TC2500a channel. Flow discharge, SSC, and TP loads at TC2500a and TC2500b were summed to give the TC2500ab combined results. The flow discharge hydrograph (obtained from the depth–discharge correlation) and the SSC record (obtained from the turbidity–SSC correlation) for the Trout Creek TC0 and TC1900 stations are shown in Figure 3a. The flow discharge for the Upper Truckee River was obtained from a USGS gauging station at UTR0. A pressure transducer at UTR2900 was dislodged by high flows, so a stage-rating curve was developed between flowmeter-derived discharge and the UTR0 stage record. The flow discharge hydrograph for UTR0 is shown in Figure 5.

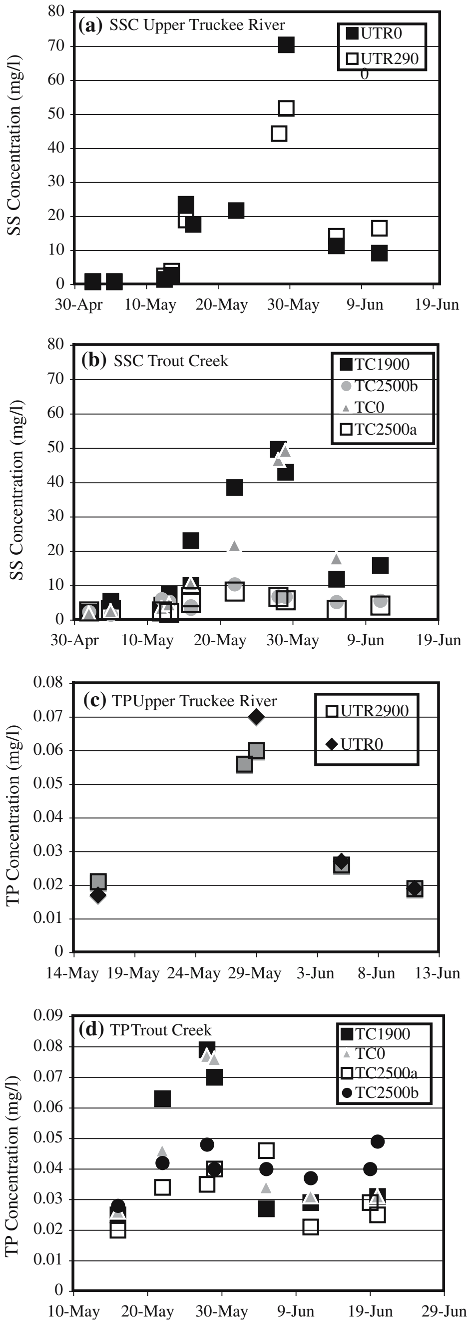

Figure 4. Depth-integrated suspended sediment and total phosphorus concentration. Samples collected with depth-integrating sampler at equal width intervals. Suspended sediment analyzed with gravimetric method. Total phosphorus analyzed with acid digestion/color spectrometry method. Total phosphorus includes particulate and dissolved forms.

The SSC record is continuous, except for a few gaps, for the TC0 and TC1900 stations for the snowmelt period (Figure 3b). Due to obstruction of the turbidometer with algae and grass, the TC2500 record was limited (Figure 3b); however, peak flow events, May 21–25 and May 27–29 were captured. The SSC record for site UTR0 (Figure 5) was complete (except for May 30, 31 and June 1). The UTR2900 record was limited for the snowmelt period owing to obstruction by floating debris and riverbank failure (Figure 5).

Sediment budgets were constructed from the turbidity record, SS correlation, and discharge data. Trout Creek shows a retention of 68–90% of SS that enters at TC0 (Table 3). Similar reductions were observed for TP, with 61–84% of the TP load entering at TC0 retained within the channel and floodplain (Table 3). Upper Truckee load retention was less, with 26% of the SS load and 24% of the TP load retained within the channel (Table 4). Total SS loading entering the study site from on Upper Truckee River for the period May 6–June 29, 2003 was 1433 tons.

Because there is a station mid-way on Trout Creek (TC1900) we can compare the moderately entrenched Upper Reach with the lower Marsh Reach (Figure 2). A direct comparison of loads is misleading, however, because some of the flow entering the study site at TC0 bypasses TC1900 via the west channel, and then rejoins the river upstream of TC2500a. The reduced load at TC1900 reflects the fact that there is less water conveyed by the channel at TC1900 than at TC0 rather than the actual retention of SS and phosphorus within the channel and floodplain. However, a comparison of concentrations, determined by dividing the SS load by the discharge over the period of measurement, gives an indication of relative retention within the Upper Reach and Marsh Reach. Greater sediment and nutrient retention were observed for water flowing through the lagoons and beaver dam-created backwater areas of the Marsh Reach. Retention of SS load per unit volume was observed to be 20–34% in the Upper Reach (between stations TC0 and TC1900), and 51–77% in the Marsh Reach (between stations TC1900 and TC2500, the sum of TC2500a and TC2500b). Reductions of TP load per unit volume were similar, with 17–28% retention for the Upper Reach (TC0–TC1900) and 43–66% retention in the Marsh reach (TC1900–TC2500).

Visual observations during peak flow events also support the conclusion that the greatest sediment retention occurred in the marsh reaches of Trout Creek. Above the lagoon, flow was observed to divide into many small channels, flowing through woody debris and small aquatic vegetation-filled pools. Overbank flows flooded large sections of marsh grass. At the site of the beaver dam (TC2500b), peak flows were diverted out of the

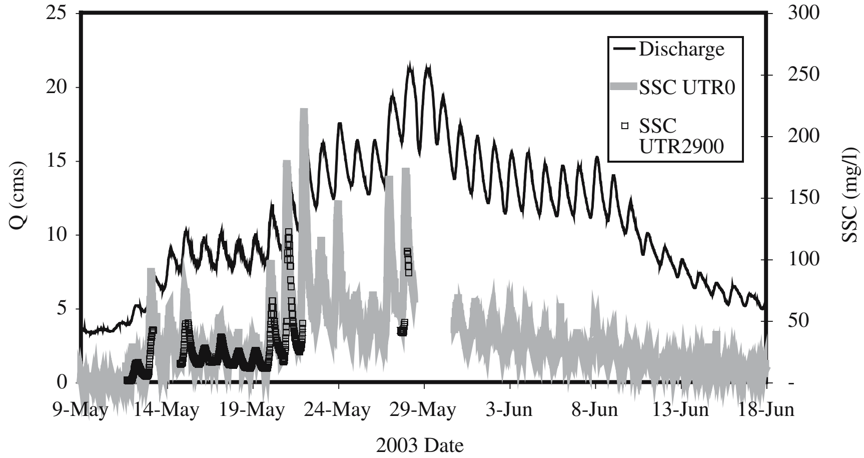

Figure 5. Hydrograph and suspended sediment concentrations for the Upper Truckee River. Suspended sediment concentration (SSC) as derived from regression of turbidometry and depth-integrated sample data. Comparison of SSC for UTR0 and UTR2900 stations indicated for entire snowmelt period. Discharge for UTR0 station. Station names indicate meters below Highway 50 bridge over Upper Truckee River.

Table 3. Trout Creek (TC) suspended sediment (SS) and total phosphorus (TP) loads.

	Time period[a]	TC0	TC 1900	TC2500[b]	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)	
TP total load (Mt)	1	5.5(−1)	2.1(−1)	n/a	
	2	7.7(−2)	3.7(−2)	3.0(−2)	61%
	3	6.4(−2)	2.1(−2)	1.0(−2)	84%
TP load per unit volume (Mt/m^3)	1	4.7(−8)	3.9(−8)	n/a	
	2	8.1(−8)	6.7(−8)	3.8(−8)	53%
	3	1.0(−7)	7.2(−8)	2.4(−8)	75%

[a] Sample period 1 was May 6 12:15 to June 17 6:15 am. Sample periods 2 and 3 are subsets of 1. They are May 21 19:45 to May 25 21:15, and May 27 21:00 to May 29 14:15, respectively.

[b] TC2500 values are the sum of TC2500a and TC2500b.

channel through grass and aquatic vegetation, before flowing in a wide splay back into the channel. Fresh deposition of sand, silt and clay-sized particles was observed in the entrance of the lagoon.

Out-of-channel retention of water in Trout Creek increased from 18% during the period May 21–25, to 34% during the period May 27–29 (Table 3). The increase is likely due to the observed flooding of large portions of the marsh during the

Table 4. Upper Truckee River suspended sediment (SS) and total phosphorus (TP) retention.

	Time period[a]	UTR0	UTR2900	Retention
Discharge (m^3)	May 12–14	682,695	560,514	18%
	May 15–16	220,306	203,564	8%
	May 16–17	944,213	887,142	6%
	May 17–22	4,748,112	4,409,636	7%
	May 28	345,222	375,075	9%
	May 29	149,547	200,589	34%
	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	20	15	26%
	May 29	22	15	32%
	Total	263	194	26%
TP load (Mg)	May 12–14	0.019	0.013	32%
	May 15–16	0.008	0.006	25%
	May 16–17	0.032	0.028	13%
	May 17–22	0.219	0.168	23%
	May 28	0.024	0.018	25%
	May 29	0.025	0.017	32%
	Total	0.327	0.250	24%

[a] Sample times are May 12 16:00; May 14 4:45; May 15 18:30; May 16 1:15; May 16 5:45; May 17 11:15; May 17 14:30; May 22 21:45; May 28 15:00; May 28 20:30; May 29 0:45; May 29 2:30.

latter period. Out-of-channel retention in the Upper Truckee River averaged 6%. Because no surface flows enter Lake Tahoe other than the ones monitored, we assume the retained water entered the groundwater, or exited from the marsh over the course of the summer at the low SS and TP concentrations observed at the end of the spring season.

Particle size in the depth integrated samples was determined by laser particle diffraction on a subset of the depth integrated samples from Trout Creek (Figure 6). During low flow periods the amount of particulates in the water was below the detection limits of the instrument. TC2500a and TC2500b had median particle sizes around 30 μm (with the exception of one reading of 56 μm, for the TC2500a station). TC0 and TC1900 stations had higher median particle sizes, in the range 30–125 μm. The data indicate that fine particle sizes are selectively retained within the study site, with the greatest retention occurring in the lower Marsh Reach (TC1900–TC2500). Greater percent retention of particles was observed in the May 28–29 samplings as compared to May 22–23 at TC1900. Analyzing the data by particle size classes (less than 1000 μm, less than 10 μm and less than

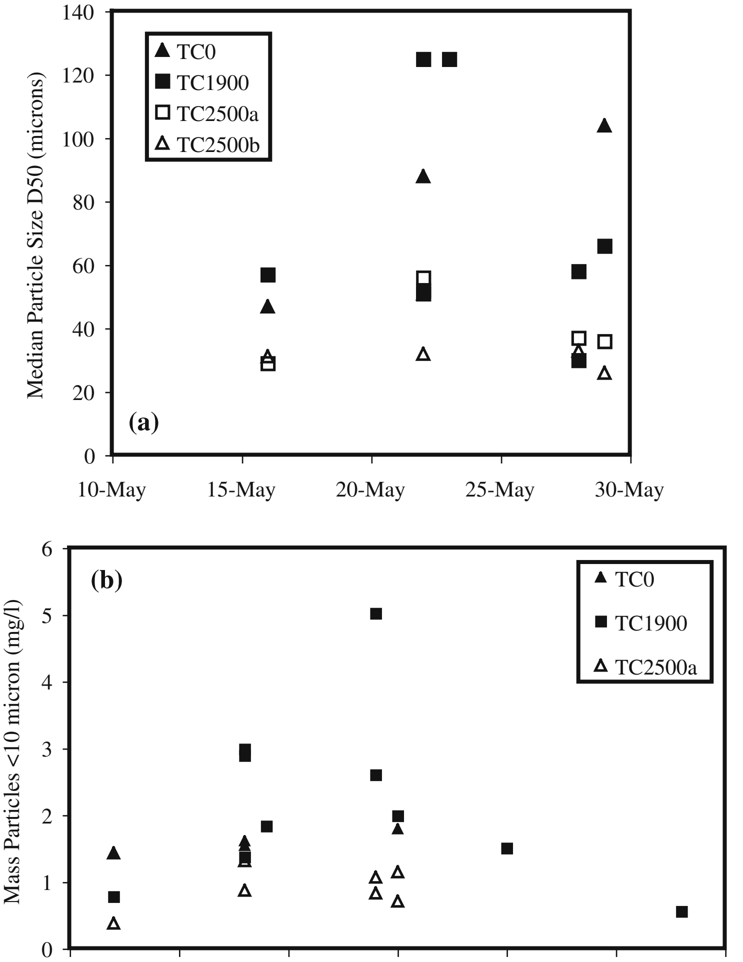

Figure 6. Trout Creek depth-integrated samples median particle size. (a) Median particle size (D50) determined using laser particle size analysis. The convention is solid = upstream; empty = downstream. Black triangle = TC0 station. Black square = TC1900. Empty square = TC2500a station. Empty triangle = TC2500b station. (b) Mass of sediments less than 10 μm. Percentiles generated by laser particle size analysis multiplied by TSS values.

1 μm), shows retention of all particle size classes within the lower Marsh Reach. The mass of particles less than 10 μm in diameter is shown in Figure 6b.

Discussion

The differences in sediment retention between the Upper and Marsh Reaches of Trout Creek reflect differences in floodplain connectivity. While both segments of river channel meander through a wide floodplain, the Upper Reach is less able to access its floodplain because it is incised. Ponding in the Marsh Reach diverts incoming floodwaters great distances out into the floodplain, where standing grasses and sedges slow water velocities leading to deposition. Cross sections shown in Figure 2 illustrate these differences in channel morphology and floodplain connectivity for the Upper and Marsh Reaches of Trout Creek. The cross sections at TC0 and TC1900 have low width to depth ratios as compared to TC2500a and TC2500b. Additionally, the cross-sectional areas of the downstream channels (TC2500a and TC2500b) are smaller.

Temporal differences support this interpretation of the role of floodplain connectivity and sedimentation. Portions of the upper floodplain were observed to be inundated as the peak flow discharge increased in the last few days of May. After May 29 a larger gap in turbidity values is apparent between the TC0 and TC1900 Stations (Figure 3b). This suggests that as water depths and floodplain connectivity increased in the upper marsh, sediment retention on the floodplain increased as well. Similarly, the retention for the Marsh Reach (TC1900–TC2500) was greater for the period May 27–29 when the marsh was filled with water, than for the earlier period May 21–25 (Figure 3b).

Incision on the upper portion of the Trout Creek may be due to bridge construction, watershed changes, or meadow alterations performed by cattle ranchers. Changes in base level from channel diversion, bridge construction, or reservoir management can result in river incision propagating upstream through head cutting and accelerated erosion at the nickpoint (Knighton 1998). Watershed disturbances such as logging, grazing, urbanization, or road construction can increase the frequency and magnitude of peak flows, resulting in channel bank erosion and downcutting (Schumm et al. 1984; Booth and Jackson 1997). In the downstream reach, the beaver dam and backwater lagoon provided a control on base level, lowering channel gradients and preventing incision.

The Upper Truckee River presents a different picture. A large straight channel was excavated to divert flows from the Tahoe Keys development. Channel cross sections for the Upper Truckee River show a low width to depth ratio, and large cross-sectional area throughout the study site (representative cross sections shown in Figure 2). This oversized channel provides no floodplain connectivity during typical flows. Furthermore, the fact that large flows are contained within the channel results in significant erosion forces on stream banks. Undercutting and bank failures were observed in 2003, introducing new sources of sediment into the channel and into Lake Tahoe. In this case, not only is the river not retaining sediment within the former marsh reach, but it also becomes a sediment source. The turbidity sensor was buried during the peak discharge event (May 23, Figure 5) when bank failures were observed. It is probable that the Upper Truckee River channel became a net source of sediment during this event, rather than the moderate retention calculated overall. Guillen and Palanques (1997) describe a similar alteration between positive and negative sediment budgets as a result of high discharge bank erosion on the Ebro river.

Lake water level is another factor determining sediment retention in the delta floodplain. During high lake levels the marsh is inundated up to a kilometer inland from the current edge shown in Figure 2. Sediment deposition can be expected to be completely different when the river mouth is effectively moved upstream. The excavated channel of the Upper Truckee River becomes an arm of the lake undergoing extensive deposition under such conditions. However, the stored material is not stabilized or trapped by vegetation as it is on a floodplain. Therefore, during low lake stands, the river rapidly downcuts the material stored in the channel bottom, delivering the sediment to Lake Tahoe.

The particle size measurements indicate efficient removal of all particle sizes measured, (1–1000 μm), in the lower reach of Trout Creek.

Field inspection indicated fresh deposits of silt and clay-sized material in the lagoon area. The data suggest that the conclusions drawn above for the spatial patterns of sediment retention are equally applicable to the smaller size classes, of particular importance to management of lake water clarity. A study of clay content in sediment cores from the Yellow River delta plain (Shi et al. 2003) found that clay was deposited equally with coarser fractions.

The factors discussed above for SS retention processes apply equally to TP. Phosphorus has been shown to stimulate algal growth in Lake Tahoe (Hatch et al. 1999). It is possible that the TP retention observed here is due to the retention of particulate phosphorus, while the concentration of more bio-available dissolved phosphorus is not affected. However, results from other areas (Stream Solute Workshop 1990; Peterson et al. 2001) indicate that the shallow depths and high surface to volume ratio of small streams (<10 m width) result in high uptake rates for dissolved nutrients relative to larger streams.

The study period was representative of high flow years. The typical snowmelt season water discharge for a period of record from 1961 to 2001, presented in Table 1, are 5.4–14.2 cms and 1.4–4.2 cms for Upper Truckee and Trout Creek, respectively (Rowe and Allender 2000; Patterson et al. 2003). The water discharge during the 2003 snowmelt season reached 20 cm on the Upper Truckee and 5 cm on Trout Creek, which are higher than the typical values. SS data indicated greater retention for the higher flows on both rivers. Low inputs have been shown on other wetlands to result in lowered retention percentage or the release of previously stored material (Kadlec 1999). Watershed loadings during low flow years, while of higher concentrations, make almost negligible contributions to Lake Tahoe loadings (Rowe et al. 2002).

Measuring turbidity proved to be an effective substitute for directly measuring SSC and TP. The disadvantage of this indirect method is balanced by the advantage of continuous measurement in a temporally variable system. The construction of a floating boom to support the turbidity sensor is recommended for larger rivers such as the Upper Truckee to accommodate the range of stage heights. For marsh environments, turbidometers with automatic wiper arms are recommended as floating grass and algal strands were found to obstruct the instrument within hours of clearing. As a result of the instrument blockage, the TC2500ab station record was quite short: one 4-day and one 2-day period. While this record is short, we feel that it is representative of the entire season for the following reasons. The record includes the largest peak flows, during which the bulk of sediment was transported. Grab sampling during other time periods indicate very little SS or TP entering the study site. Retention rates for the Upper Reach are calculated from a 41-day record. However, if we only use the same 2- and 4-day time periods that the Marsh Reach sensor was operational, we get similar results as the full 41-day period.

This study shows the important role that wetlands serve to buffer land uses detrimental to aquatic ecosystems. A database of treatment wetlands performance (Knight et al. 1993) gives SS and TP load retentions for 69 free water surface wetlands. The wetlands in the database, in comparison to Trout Creek marsh reach, had lower discharges (2159 m^3/day vs. 120,000–360,000 m^3/day for Trout Creek), had less area (32.6 ha vs. 400 ha for the Trout Creek–Upper Truckee Marsh), had phosphorus concentrations an order of magnitude higher than the Trout Creek values, and were based on monthly sampling. The treatment wetlands retention rates were 69% for SS load and 55% for TP load, which are similar to the 68–90% and 61–84% measured in this study for Trout Creek. In a summary of fluvial sediment storage in ten wetlands, Phillips (1989) found a range of retention rates of 23–91%, with larger (>100 km^2) watersheds having greater retention. A study of marsh wetlands in Washington found SS removal rates of 14% for an urban wetland, and 56% for a non-urban wetland (Reinelt and Horner 1995). TP removal rates were $\sim$80% for both wetlands.

Comparisons can also be made to delta sedimentation studies, although most are for much larger river systems. Shi et al. (2003) found that 74% of fluvial sediment was trapped on the delta front and delta plain of the Yellow River. Goodbred and Kuehl (1998) report that 30–40% of fluvial sediment below the lowest gauging station on the Ganges–Brahmaputra delta was trapped on the delta plain. Syvitski et al. (2005) gives retention rates of 20%, 55% and 82% for the Amazon, Ganges and Yellow River deltas, respectively. These numbers represent delta plain storage combined with subaqueous storage on the delta slope and prodelta. Dirszowsky and Desloges (2004) report that for the fine fraction ($< 63\ \mu$m) of Holocene fluvial sediment entering Moose Lake in British Columbia, 8% was deposited on the delta plain, with the rest distal lake bottom storage.

Soil cores taken from the marsh in previous studies, at portions flooded by Trout Creek, have indicated mass sedimentation rates in the last 49 years of 0.46 g $\mathrm{cm^{-2}\ yr^{-1}}$ (Winter 2003) and within ranges of 0.09–0.38 g $\mathrm{cm^{-2}\ yr^{-1}}$ for Pope Marsh to the west (Kim and Rejmankova 2001). Given that very little overbank flow was observed, the 2003 mass sedimentation rate was not calculated for the Upper Truckee River. The 2003 mass sedimentation rate for Trout Creek, using the largest retention value of 90% (Table 3) and a flooded marsh area of 80 ha, was 0.029 g $\mathrm{cm^{-2}\ yr^{-1}}$. This value is approximately 5% of the long-term average determined from soil coring for the 46-year period at this site. The average value determined by soil coring is higher than the 2003 values likely as a result of higher sedimentation occurring during major flood events. The TP removal rate may be calculated in the same manner as the mass sedimentation rate for Trout Creek. Using the highest measured retention percentage (84%), on the 2003 TP input (0.547 *t*) gives 0.23 g $\mathrm{m^2\ yr^{-1}}$. This result is below the threshold value of 1 g $\mathrm{m^2\ yr^{-1}}$ determined from a database of 100 wetlands to be a limit to the TP assimilative capacity of a wetland (Richardson et al. 1997). TP removal rates above this threshold resulted in sharply rising output concentrations. The results suggest the assimilation capacity of the Trout Creek marsh is not exceeded by current watershed inputs.

Insight into the magnitude of SS and TP retention taking place on the Upper Truckee River before the canalization may be inferred from the rates measured for Trout Creek. The SS and TP load exiting the Upper Truckee helps to explain the decline in the clarity of Lake Tahoe over the last four decades, and provides an indication of the water quality improvements that may be expected from restoration of the Upper Truckee River. Aerial photographs suggest that the original Upper Truckee River channel bifurcated into many small distributaries within the original marsh, as is commonly observed for floodplain deltas. Patterson et al. (2003) found the percentage of cross sections on a 1940 aerial photograph of the Upper Truckee River classified as single thread channel, split main channel, side channels, and non-active channel was 47-47-6-0. This classification is similar to that determined for Trout Creek from a 2002 photograph: 40-40-20-0. In contrast, the classification of the 2002 Upper Truckee River was 71-0-0-29.

To the extent that Trout Creek and the predisturbance Upper Truckee River are comparable, overall retention rates measured on Trout Creek may be applied to the measured input load to the Upper Truckee reach to estimate the magnitude of the effect the channelization had on loading rates to Lake Tahoe. For the 2003 snowmelt (6 May–29 June) our data indicate that 917 tons of suspended sediment would have been prevented from entering Lake Tahoe if the Upper Truckee River remained in its original channel morphology. As the Upper Truckee River is the largest single inflow into Lake Tahoe (Rowe et al. 2002) it is likely that the loss of wetland function from this channelization had a substantial effect on the clarity of Lake Tahoe, and restoration efforts to improve floodplain connectivity would be rewarded in improved clarity.

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