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NUTRIENT AND SEDIMENT PRODUCTION, WATERSHED CHARACTERISTICS, AND LAND USE IN THE TAHOE BASIN, CALIFORNIA-NEVADA[1]

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ABSTRACT: In efforts to control the degradation of water quality in Lake Tahoe, public agencies have monitored surface water discharge and concentrations of nitrogen, phosphorus, and suspended sediment in two separate sampling programs. The first program focuses on 20 watersheds varying in size from 162 to 14,000 ha, with continuous stream gaging and periodic sampling; the second focuses on small urbanized catchments, with automated sampling during runoff events. Using data from both programs, we addressed the questions (1) what are the fluxes and concentrations of nitrogen and phosphorus entering the lake from surface runoff; (2) how do the fluxes and concentrations vary in space and time; and (3) how are they related to land use and watershed characteristics? To answer these questions, we calculated discharge-weighted average concentrations and annual fluxes and used multiple regression to relate those variable to a suite of GIS-derived explanatory variables. The final selected regression models explain 47-62% of the variance in constituent concentrations in the stormwater monitoring catchments, and 45-72% of the variance in mean annual yields in the larger watersheds. The results emphasize the importance of impervious surface and residential density as factors in water quality degradation, and well-developed soil as a factor in water quality maintenance.

(KEY TERMS: Lake Tahoe; nonpoint source pollution; multiple regression; total maximum daily load; watershed management; nitrogen; phosphorus; sediment.)

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INTRODUCTION

Lake Tahoe, a large ultra-oligotrophic lake in the Central Sierra Nevada, is world-renowned for its clarity and deep blue color. Over the last half-century, parts of the lake basin have been developed for residential and commercial use, and the lake has undergone progressive eutrophication and loss in clarity. The growing water quality problems of the lake have been studied intensively since the early 1960s (Goldman, 1981), and have attracted considerable political attention. In spite of increased land use controls and export of treated sewage effluent from the

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basin, primary productivity of the lake is increasing by more than 5% annually, and its clarity is decreasing at an average rate of 0.25 m/years (Jassby *et al.*, 1999; Reuter *et al.*, 2003).

In efforts to understand the sources of water quality degradation and to help formulate policies to slow or halt the degradation, state and federal agencies have embarked on an ambitious total maximum daily load (TMDL) program to measure the flux of nutrients and sediment to the lake, identify their sources, and simulate lake water clarity response to pollutant load reduction using a customized water quality model (Swift *et al.*, 2006). The database on watershed sources includes over 400 station-years of discharge and water quality data at gaging stations on major tributaries to the lake, as well as recent short-term records of stormwater discharge and event mean concentrations (EMCs) at urbanized sites. These data allowed us to approach the questions: (1) what are the total fluxes of nitrogen, phosphorus and sediment to the lake from surface discharge, (2) how do the fluxes and concentrations vary over time, and (3) how are watershed yields and constituent concentrations related to watershed characteristics and land use patterns in the basin? The answers to these questions will (1) provide a basis for improving nutrient and sediment budgets for the lake and watersheds; (2) help to identify problem areas, and focus on treatment approaches; and (3) provide input and verification of results for water quality models being used in the Lake Tahoe TMDL (e.g., Riverson *et al.*, 2006; Swift *et al.*, 2006).

To answer the questions posed above, we (1) calculated discharge-weighted mean concentrations and annual loads for tributary flow, from daily discharge and water chemistry records at 20 gaging stations, for three forms of nitrogen, two forms of phosphorus, and suspended sediment (SS); (2) calculated EMCs of nitrogen, phosphorus, and SS for about 450 complete storm-flow events, during 2003 and 2004, at 19 automated sampling stations; (3) analyzed information on land use and watershed characteristics in the sampled catchments, in geographic information system (GIS) format; and 4) tested hypotheses about relationships between water quality, watershed characteristics and land use, using multiple regression.

Since the late 1960s, when concern developed about the progressive eutrophication of Lake Tahoe, there have been at least three attempts to explain the variation in water quality in terms of watershed characteristics and land use. Brown *et al.* (1973) collected monthly water samples and measured discharge in 22 streams in and around the Tahoe basin. Their final equations (which varied by season) accounted for up to 75% of the variance in sediment production, 90% of the total nitrogen (TN) production, and 93% of the orthophosphate production. The percent urbanized area and percent in ski areas entered the regression equations for TN and sediment, with contribution depending on flow season.

Byron and Goldman (1989) used a system of land capability classification developed as a regulatory tool for the Tahoe basin (Bailey, 1974) to examine the relationship between disturbance and water quality. With data from 10 watersheds, they used simple linear regression to relate discharge-weighted mean concentrations of nitrate-N, soluble reactive phosphorus (SRP), total phosphorus (TP), and suspended sediment concentration (SSC) to the percentage of watershed in disturbed high-hazard or disturbed low-hazard lands. They found significant positive relationships for nitrate-N, TP, and SSC with percent disturbed high hazard lands, and for SRP and TP with percent disturbed low hazard lands. Hazard classes were based on a geomorphic classification of the Tahoe Basin (Bailey, 1974) that takes account of slope, soil erodibility, and proximity to stream channels.

Most recently, Hatch *et al.* (2001) tried relating concentrations and loads of TP, dissolved organic P, and SRP to watershed characteristics and land use in the Tahoe basin, using linear univariate regression with data from nine watersheds. They found that aerial SRP load (kg/ha/years) was related to percent moderate hazard lands and that SRP concentration was positively related to road density and negatively related to drainage density. Streambank erosion was thought to be a major source of TP and SS. Aside from these three studies, we are not aware of any previous attempts to use multivariate methods to relate water quality to watershed characteristics in partially urbanized subalpine watersheds.

STUDY AREA AND METHODS

Lake Tahoe lies at an elevation of 1898 m in the central Sierra Nevada, astride the California-Nevada border (Figure 1). Volume of the lake is 156 km^3, and its surface area is 501 km^2, 38% of the total basin area of 1,313 km^2 (including the lake surface area). Mean annual precipitation (MAP) ranges from over 140 cm/years in watersheds on the west side of the basin to about 67 cm/years near the lake on the east side of the basin (Daly *et al.*, 1994; see Figure 2). Most of the precipitation falls as snow between November and April, although rainstorms combined with rapid snowmelt account for the highest flows and occasional floods. There is a pronounced annual runoff of snowmelt in late spring and early summer, the timing of which varies from year to year and by

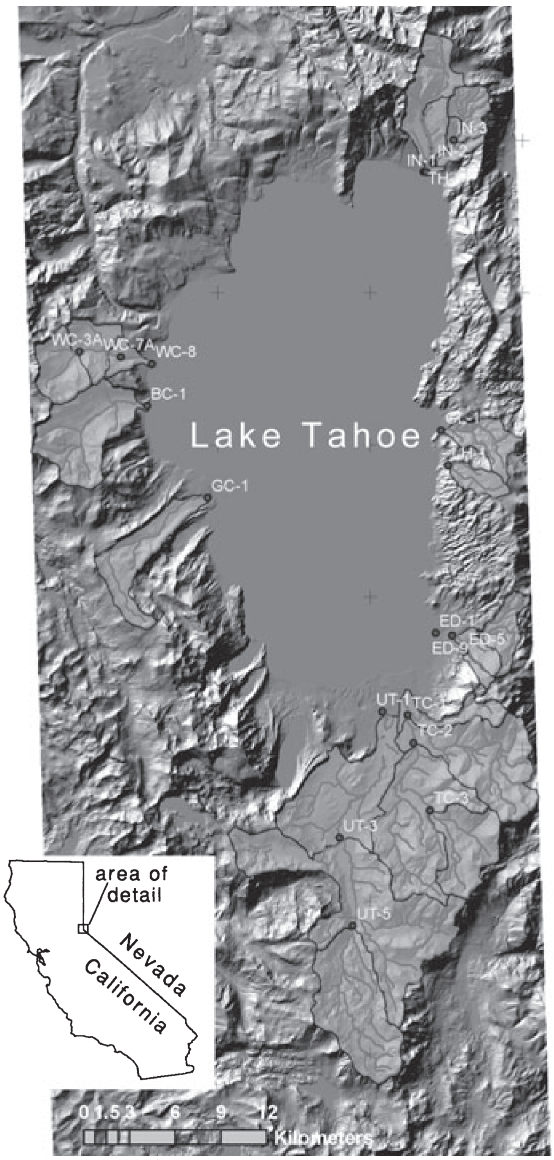

FIGURE 1. Map of the Tahoe Basin, With Locations of Stations Listed in Table 1.

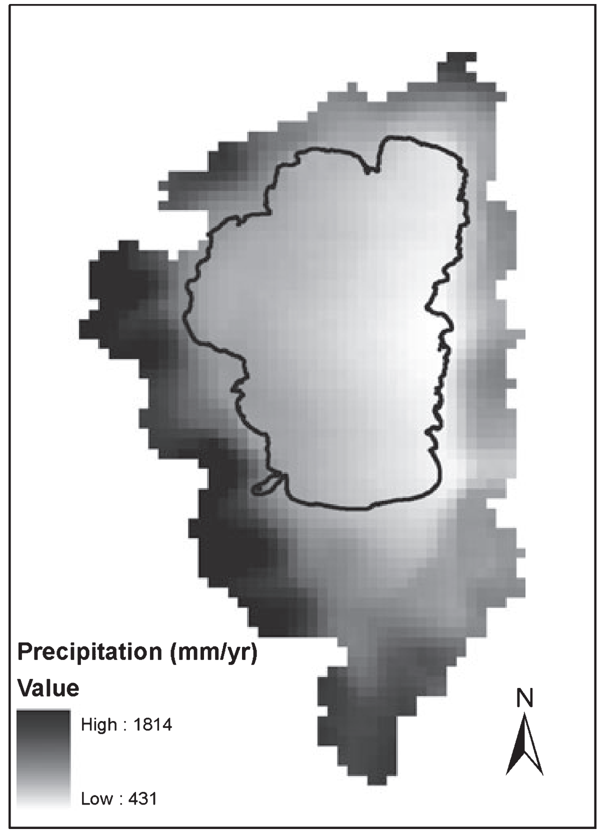

FIGURE 2. Mean Annual Precipitation in the Tahoe Basin, Based on the PRISM Model (Daly *et al.*, 1994).

location in the Basin. In some years, summertime monsoonal storms from the Great Basin bring intense rainfall, especially to high elevations on the east side of the basin.

Vegetation in the basin is dominated by a mixed conifer forest of Jeffrey pine (*P. Jeffreyi* Grev. and Balf.*)*, lodgepole pine (*P. murrayana* Grev. and Balf.), white fir (*Abies concolor* Lindl.), and red fir (*A. magnifica* A. Murr.). The basin also contains significant areas of wet meadows and riparian areas, dry meadows, brush fields (with *Arctostaphylos* and *Ceanothus*) and rock outcrop areas, especially at higher elevations. *Ceanothus* is capable of fixing nitrogen, but mountain alder (*Alnus tenuifolia* Nutt.), which grows along many of the basin's streams, springs and seeps, fixes far greater quantities, and contributes measurably to nitrate-N concentrations in some small streams (Fleschner, 1975; Leonard *et al.*, 1979).

Soils of the basin are derived primarily from andesitic volcanic rocks and granodiorite, with minor areas of metamorphic rock. Some of the valley bottoms and lower hillslopes are mantled with glacial moraines, or glacial outwash material derived from the parent rock. Cryopsamments, Cryumbrepts, rockland, rock outcrops, and rubble and stoney colluvium account for over 70% of the land area in the basin. The basin soils (in the <2 mm fraction) are generally 65-85% sand (0.05-2.0 mm) (Rogers, 1974).

Substantial areas of the basin have been developed for residential and commercial uses, especially along the north, south, and west shores. The rate of development was especially intense during the 1960s and 1970s, but has since slowed due to land use controls.

The Lake Tahoe Interagency Monitoring Program

Sampling and Analysis. From 1972 to 1978, the University of California-Tahoe Research Group (TRG) sampled up to four streams in the Tahoe basin. Since water year (WY) 1980, the Lake Tahoe Interagency Monitoring Program (LTIMP) has increased the number of stations, sampling at up to 21 stations and measuring the concentrations of nitrate-N, SRP, TP, SSC, iron, and (since WY 1989) Total Kjeldahl Nitrogen (TKN). Ten of the sampling stations are near tributary mouths. Between 1990 and 1992, the LTIMP program added two upstream stations each on 5 of the 10 streams with primary stations (See Table 1). Discharge from the monitored LTIMP streams accounts for about 50% of tributary inflow to the Lake. Figure 1 shows the Lake Tahoe basin, with the LTIMP sampling stations indicated. The five streams with stations on upstream tributaries are Ward, Trout, Upper Truckee, Trout, and Incline Creeks.

Discharge at each of the LTIMP tributary monitoring stations is measured by the United States (U.S.) Geological Survey (USGS), using continuous water level recorders, together with cross-section surveys and velocity measurements for developing rating curves. Samples of stream water are collected for nutrient and sediment analysis at the stream gaging stations, according to protocols of the USGS (U.S. Geological Survey, 1998). Sampling frequency is largely event-based and dependent on runoff conditions. During spring snowmelt, samples are collected at least weekly, with up to two samples per day during high runoff. During large precipitation events, an attempt is made to collect two or three samples, ideally representing the rising stage, hydrograph peak, and the falling stage. During low flow periods in fall, winter and mid-summer, samples are collected approximately monthly. The frequency of sampling at LTIMP stations has varied over the years of the program, declining from >100 samples per year per station in the mid-1980s to about 30 samples per year per station at present. The LTIMP sampling program is described in more detail in Rowe *et al.*, 2002.

Since 1988, samples have been collected with a USGS DH81 depth-integrating sampler, using the Equal Width Increment method. Samples from intervals across the stream are composited in a churn splitter, and allocated to bottles for later analysis. Prior to 1988, single grab samples were collected at each site and time.

Samples for inorganic nitrogen analysis are filtered on-site through a 0.45-μm filter, returned to a laboratory at the Lake, and stored at 4°C for usually no more than 7 days prior to analysis. Nitrate-nitrogen is determined by the hydrazine reduction method of Kamphake *et al.* (1967), and ammonium-nitrogen by the indophenol method of described by Liddicoat *et al.* (1975) and Solorzano (1969). Samples for organic nitrogen are shipped in a cooler to a laboratory at the University of California at Davis. Unfiltered samples are subjected to Kjeldahl digestion followed by direct colorimetric determination of ammonium (as above). SRP is analyzed by the

TABLE 1. LTIMP Sampling Stations, With USGS Site Name and Station Number, and Period of the Water Quality Record (to present unless indicated otherwise).

LTIMP Name	Site Description	USGS Code	Period of WQ Record
BC-1	Blackwood Creek near Tahoe City, CA	10336660	1974
ED-1	Edgewood Creek at Lake Tahoe near Stateline, NV	10336765	1989-1992
ED-3	Edgewood Cr. at Palisade Dr. nr Kingsbury	103367585	1990
ED-5	Eagle Rock (W. Edgewd.) Cr. abv H_2O tank	103367592	1990-1900; 2002
ED-9	Edgewood Creek at Stateline	10336760	1993
GC-1	General Creek near Meeks Bay, CA	10336645	1980
GL-1	Glenbrook Creek at Glenbrook, NV	10336730	1980
IN-1	Incline Creek near Crystal Bay, NV	10336700	1988
IN-2	Incline Creek blw golf course/at HWY 28	103366995	1990
IN-3	Incline Creek abv Tyrol Dr. abv trib	103366993	1990
LH-1	Logan House Creek near Glenbrook, NV	10336740	1988
TC-1	Trout Creek at South Lake Tahoe	10336780	1988
TC-2	Trout Creek at Pioneer Trail nr S.L. Tahoe	10336775	1980
TC-3	Trout Cr. at USFS Rd 12N01 nr Meyers, CA	10336770	1990
TH-1	Third Creek near Crystal Bay, NV	10336698	1988
UT-1	Upper Truckee River at South Lake Tahoe, CA	10336610	1980
UT-3	Upper Truckee R. at HWY 50 abv Meyers, CA	103366092	1990
UT-5	Upper Truckee R. at S. Upper Truckee Rd.	10336580	1990
WC-3A	Ward Creek below confluence	10336674	1992
WC-7A	Ward Cr. near Stanford Rock Trail blw Page Mdws.	10336675	1992
WC-8	Ward Creek at HWY 89 near Tahoe Pines	10336676	1972

Note: LTIMP, Lake Tahoe Interagency Monitoring Program.

ascorbic acid method (Murphy and Riley, 1962). TP is analyzed by the same method following persulfate digestion (Menzel and Corwin, 1965). SS is analyzed as SSC (ASTM D 3977-97; Guy, 1969).

In 1995, samples from 9 of the 10 LTIMP streams (excluding Edgewood Creek) were analyzed for total dissolved phosphorus (TDP), as well at TP and SRP, with 30-50 samples per station (Hatch *et al.*, 1999). For comparison with total suspended sediment (TSS), particulate phosphorus (PP) for the nine streams was calculated by subtracting TDP from TP, using discharge-weighted averages. The PP:TP ratio for each stream was then used in this study to estimate PP from TP.

Method detection limits (MDL) for the three forms of nitrogen are 2 μg/l for nitrate-N, 3 μg/l for ammonium-N, and about 35 μg/l for TKN (Janik *et al.*, 1990). For SRP and TP, the MDL is 1 μg/l, with a precision of ±0.6 μg/l. QA/QC procedures (use of field blanks, spike recovery, duplicate samples, etc.) conform to USGS protocols (Janik *et al.*, 1990).

It has been known for some time that the hydrazine reduction method for nitrate analysis in a stream water matrix is subject to chemical interference, apparently from divalent cations (Ca^{2+} and Mg^{2+}) and dissolved oxygen (Kempers and Luft, 1988; Kempers and Van Der Velde, 1992). The method has been modified with the addition of pyrophosphate to reduce the interference, and since 2003 the LTIMP samples have been analyzed by both the old and the modified method. In order to correct the old data, a set of 575 streamwater samples analyzed in 2003-2004 by both the modified and unmodified methods was used to develop linear regression equations for each of the 10 primary (watershed mouth) station (R^2 = 0.76-0.99; SE = 2-27 μg/l). These equations were then used to adjust the nitrate concentration from that measured by the unmodified method to an estimate of the concentration measured by the modified method.

In analyzing data in which some concentrations are reported as less than the "method detection limit," some value between 0 and the MDL must be assigned (Helsel and Hirsch, 1995). It was assumed that concentrations are log-normally distributed between the MDL and 0. Concentrations to fit such a distribution were approximated by taking MDL × (square root of a random number between 0 and 1). Values reported as "<MDL" were replaced by a number so assigned. Two-thirds of the ammonium-N, <3% of the TKN and SS, <1.5% of the nitrate-N, and, <1% of the TP and SRP determinations were below the MDL. As so many of the ammonium-N determinations were less than the MDL in the LTIMP streams, these data were excluded from the statistical analysis.

Discharge-Weighted Mean Concentration. Since some of the LTIMP stations are located upstream from others in the same watershed, the data from the upstream and downstream stations do not represent independent sample sets. Water quality at both stations is influenced by watershed conditions above the upper station. We created a dataset of discharge-weighted mean concentrations (C_{Qwtd}) that represents samples from independent watershed subareas using the following formula

$$C_{\mathrm{Qwtd(b)}} = \sum \frac{C_{\mathrm{i(b)}} \times Q_{\mathrm{i(b)}} - C_{\mathrm{i(a)}} \times Q_{\mathrm{i(a)}}}{Q_{\mathrm{i(b)}} - Q_{\mathrm{i(a)}}}, \tag{1}$$

where C_{i} is the instantaneous concentration in the ith sample at a station, Q_{i} is the instantaneous discharge at the time of sampling, and (a) and (b) refer to the upstream and downstream stations. We then filtered the data to remove sample pairs that were collected more than three hours apart. The final dataset comprised 3,744 samples or pairs of samples for 1993-2000.

The method of removing the influence of the upper watershed areas from the downstream stations makes a number of assumptions. First, it assumes that a water quality parameter is conservative between stations over a period of up to three hours. This may apply for the dissolved constituents, but sediment (as well as the other the particulate constituents) may be deposited or mobilized between stations, especially during the snowmelt season when discharge is elevated and changing rapidly. Second, it assumes that the same water mass at both stations is being sampled when samples are collected within a three-hour period. Conditions that violate these assumptions are considered to contribute to the overall sampling error.

Constituent Load and Yield Calculations. In the Tahoe basin, interest is focused on the constituent loads to the lake, on time scales of months and years. Constituent loads were calculated by two separate methods. Loads of the dissolved constituents– ammonium-N, nitrate-N, and soluble reactive P (SRP) – were calculated by a modification of the period-weighted sample (PWS) method, which has been shown to give more accurate and precise estimates of annual loads for dissolved constituents in Tahoe basin streams than regression of concentration with discharge, especially with <40 samples per year (Coats *et al.*, 2002). Additionally, TP and TKN loads were also calculated using this method and later compared with regression methods. Daily concentrations were interpolated from the data using a cubic spline interpolation (Venables and Ripley, 1996). The daily concentrations were then multiplied by mean daily discharge (from the USGS gaging station records), and the products (daily load) were summed over each year and station.

The particulate constituents – TP, TKN, and SS – were primarily calculated by regression. Log of instantaneous concentration was regressed against two discharge variables: log of mean daily discharge, and cumulative discharge, as a fraction of total discharge for the WY. The latter was found in trials with the Blackwood Creek data to significantly improve the predictive ability of the regressions. In addition, the quadratic and interaction terms of log of daily discharge and cumulative discharge were included in the regression models. Predicted concentrations were corrected for retransformation bias (Ferguson, 1987). The programs for calculating total loads were written in S-Plus at the University of Nevada Reno, Department of Mathematics and Statistics.

For TP and TKN, the choice of methods was based on the regression results for each WY and station; where the multiple R^2 was <0.6, the PWS estimate was used instead of the regression estimate. Regression was used in all cases for SS.

The Stormwater Monitoring Program

In support of the Lake Tahoe TMDL program, nineteen monitoring sites were established in ephemeral drainages with various degrees of urban development around Lake Tahoe. Twelve stations were established in fall of 2002 by the University of California Davis Tahoe Research Group (TRG) and the Desert Research Institute. In 2003, seven stations were added to the network. Figure 3 is a map of Lake Tahoe with stormwater monitoring (SWM) site locations. Table 2 shows the full site names and the abbreviations.

All SWM sites were equipped with an automated sampler with a capacity of 24 1-l bottles and a datalogger. The autosamplers are triggered by a predetermined stage height or a preset volume. The height, volume, and frequency at which sampling is triggered differs at each site depending on the typical site flow conditions. EMC were calculated for each runoff event. Each event is characterized by hydrologic type, e.g., rain, rain-on-snow, snowmelt, or thunderstorms. Except during snowmelt, most sites did not flow during intervals between events.

Samples from the SWM program were measured for the same constituents as the LTIMP samples, with the addition of TDP. PP was calculated from discharge-weighted averages as the difference between TP and TDP. Sediment was measured and reported as TSS (U.S. Environmental Protection Agency

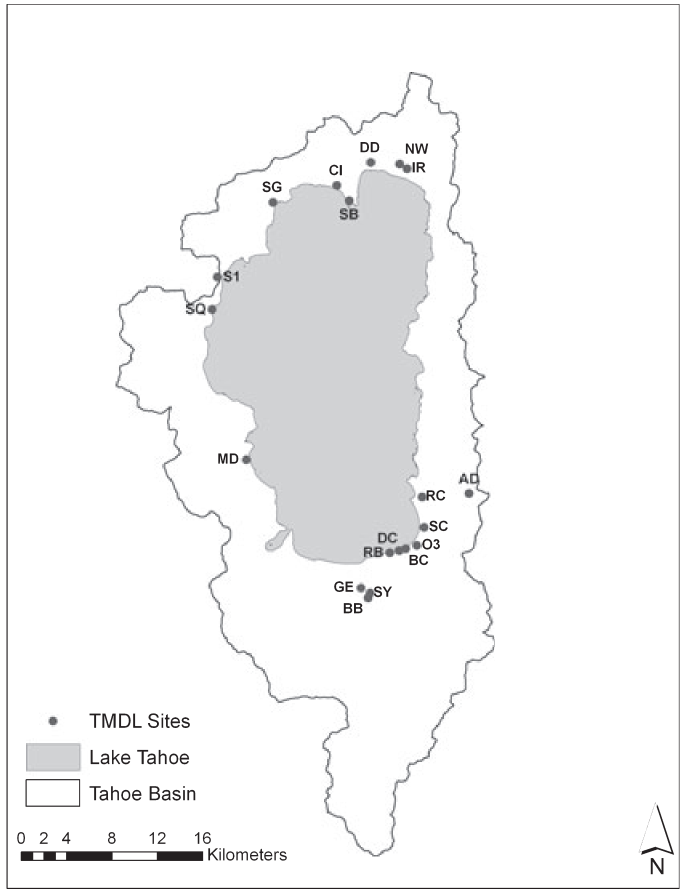

FIGURE 3. Map Showing the Locations of the Stormwater Monitoring (SWM) Sites of the Total Maximum Daily Load (TMDL) Program. Letter abbreviations refer to place names in Table 2.

Method 160.2; Clesceri *et al.*, 1989). The modified (pyrophosphate) method was used in nitrate-N analysis for all of the SWM samples.

To calculate EMCs for storms and snowmelt pulses, the event samples were composited, with the volume contributed from each sample proportional to the discharge at the sample time. For both WYs (individually and together), the discharge-weighted (Q-wtd) mean concentration was calculated at each monitoring site. The Q-wtd mean concentration is calculated using the following formula

$$\text{Q-wtd mean concentration} = \frac{\sum(Q_\mathrm{i} \times \mathrm{EMC_i})}{\sum Q_\mathrm{i}}, \tag{2}$$

where, Q_i is the discharge of runoff event "i," $\mathrm{EMC_i}$ is event mean concentration of event "i." Since the constituent concentrations were often much higher during thunderstorms than during snowmelt and frontal rainstorms, the thunderstorm data were treated separately; regression analysis was applied only to the non-thunderstorm data.

TABLE 2. The Stormwater Monitoring Sites.

Stormwater Monitoring Sites				Percent Land Use by Category						Residential Lot Density		Catchment Characteristics			
Site Name	Code	Date Began	Date Ended	SFR	MFR	CICU	RDS	VEG	RESIMP	D-SFR	D-MFR	IMP	Slope (%)	MAP (cm)	Area (ha)
Andria Dr.	AD	5 Dec 02	9 Mar 04	68	0	0	22	9	14	2.8	0.0	37	43	74.2	5.80
Bonanza Ave.	BB	9 Dec 02	16 Feb 04	41	14	2	14	29	19	1.6	3.9	10	59	61.4	37.05
Bijou Creek	BC	1 Aug 03	9 Jun 04	15	2	1	4	77	5	4.8	5.1	34	14	63.1	464.50
Coon Street	CI	1 Oct 02	16 Feb 04	40	24	1	19	16	16	4.0	11.8	35	21	59.7	9.47
Don Cheapo's	DC	13 Mar 03	28 May 04	0	0	76	24	0	0	0.0	0.0	95	3	58.4	1.21
Dale Dr.	DD	6 Dec 02	27 Mar 04	67	0	0	20	13	13	1.3	0.0	33	64	57.9	11.67
Glorene & 8th	GE	1 Dec 04	11 May 04	3	0	77	16	4	1	56.2	0.0	66	8	60.9	0.41
IV Raley's	IR	19 Dec 02	9 Jun 04	0	32	55	7	6	0	0.0	4.0	46	23	50.0	10.88
Mountain Dr.	MD	1 Dec 02	16 Feb 04	62	0	0	18	19	17	5.3	0.0	35	75	112.6	1.85
Northwood	NW	9 Dec 02	10 May 04	67	2	6	13	12	14	0.4	9.8	28	36	51.0	29.09
Osgood Ave.	O3	10 Feb 03	28 May 04	23	38	2	24	13	23	10.2	5.8	48	14	58.1	9.68
Regan Beach	RB	24 Feb 03	9 Jun 04	41	22	3	21	13	23	6.1	7.5	45	3	57.0	19.66
Roundhill CDS	RH	13 Dec 02	1 May 04	74	0	1	9	14	14	1.2	4.7	24	67	65.2	32.04
TCWTS	S1	1 Oct 02	10 May 04	20	18	24	21	17	17	6.0	7.6	59	27	82.5	22.83
Speedboat Ave.	SB	24 Oct 02	11 May 04	34	3	22	20	21	7	4.5	3.2	43	45	55.7	16.55
SLT Casinos	SC	1 Jul 03	19 May 04	0	0	77	4	18	0	0.0	17.6	71	16	70.5	42.62
Shivagiri	SG	1 Mar 04	19 May 04	0	0	0	0	100	0	3.4	0.0	0	51	86.5	99.46
Sequoia Ave.	SQ	7 Nov 02	25 Mar 04	53	11	0	16	20	13	1.6	8.4	29	27	79.8	6.69
SLT-Y	SY	13 Feb 03	27 May 04	14	9	44	13	19	7	4.3	3.7	53	4	62.9	14.75

Notes: SFR, single family residential; MFR, multiple family residential; CICU, commercial/industrial/communications/utilities; RDS, paved roads; VEG, vegetated; RESIMP, residential impervious; IMP, impervious percent; MAP, mean annual precipitation. Density of SFR and MFR was calculated as number of lots divided by total lot area in the catchment.

Analyzing Watershed Attributes

The Tahoe Environmental GIS (Cartier *et al.*, 1994) was modified and used to generate information about the watersheds and subwatersheds represented in both the LTIMP and SWM water quality sampling program (Luck *et al.*, 2002). This was carried out using the following steps: (1) the vector-based layers were converted to a raster (pixel)-based format; (2) the boundaries of the subwatersheds were defined, based on the station locations and 10-meter Digital Elevation Model (DEM); and (3) a preliminary list of independent variables was developed, based on professional knowledge of variables that could be expected to contribute to the loads and concentrations of the water quality constituents. Table 3 lists and defines the explanatory variables derived for the LTIMP watersheds, and Table 4 lists the variables derived for the SWM catchments; (4) the value for each variable was calculated for each subwatershed, in ArcView (Environmental Systems Research Institute, Redlands, CA).

For the LTIMP watersheds, mean slope was calculated by averaging (across each watershed) the percent slope calculated at each pixel in the DEM. For both the LTIMP watersheds and the SWM catchments, the percent impervious surface for each land use category was calculated from recent IKONOS satellite coverage for the Tahoe basin (Minor and Cablk, 2004). The images were filtered and partially masked to eliminate areas of rock outcrop. The percent impervious surface in a watershed is a useful predictor of cumulative hydrologic and water quality impacts of development (Arnold and Gibbons, 1996; Jones *et al.*, 2001; Groffman *et al.*, 2004).

Multiple Regression Methods

We approached the problem of finding the best multivariate models to explain the variance in volume-weighted concentration and watershed yields in several steps, using the programs in the NCSS software package (Hintze, 2001). First, we screened the variables listed in Tables 3 and 4 using the matrix of Pearson correlation coefficients to identify and eliminate variables where the correlation coefficient exceeded 0.7. To further reduce collinearity and to find candidate models, we used an "all possible regressions" routine in NCSS. The variable sets that maximized the R^2 and produced a Mallows's Cp close to $p + 1$, p being the number of explanatory variable in the regression equation, were then selected for further consideration. Mallows's Cp statistic is a measure of the "goodness of fit" of a regression model. It provides a way of finding a compromise between maximizing R^2 with many variables (many of which contribute only marginally to explaining the total variance),

TABLE 3. Definitions of Watershed Explanatory Variables Derived From GIS and Tested in Statistical Analysis of LTIMP Yield and Concentration Data.

No.	Variable Name	Code	Units	Definition and Source of Information
1	Area	area	km^2	Luck *et al.*, 2002
2	Stream Length	strlen	km	Luck *et al.*, 2002; from USGS 1:24,000 scale maps
3	River Length	rivlen	km	Luck *et al.*, 2002; from USGS 1:24,000 scale maps
4	Riparian River	ripriv	km	Luck *et al.*, 2002; Rivers intersecting with riparian vegetation
5	Alluvial River	allriv	km	Luck *et al.*, 2002; Rivers intersecting with alluvium in soils map
6	Riparian and Alluvial Rivers	alrip	km	Sum of variables 4 and 5
7	Unweighted Slope	unwtdsl	%	Luck *et al.*, 2002; from 10 m Digital Terrain Model (DTM)
8	Mean Ann. Precip.	map	cm	Mean Annual Precipitation, from PRISM model; (Daly *et al.*, 1994).
9	River Density	rivden	km/km^2	from 3 and 1, above
10	Riparian River Pct.	riprivpct	%	from 3 and 4, above
11	Alluvial River Pct.	allrivpct	%	from 3 and 5, above
12	Pct. Volcanic	pctvol	%	Luck *et al.*, 2002; Percent of soils derived from volcanic rock.
13	Pct. Granitic	pctgran	%	Luck *et al.*, 2002; Percent of soils derived from granitic rock.
14	Soil Index	soilindex	–	Luck *et al.*, 2002 and Rogers, 1974 soils map. Unsuitable and unclassifed sites (Rockland, etc.) were assigned site class = 6, and the soil index defined as $-X + 6$, where X = forest site class
15	ln(Soil Index)	lnsoilindex	–	Natural log of Soil Index
16	Low Intensity Residential	lowintres	%	USGS National Land Cover Database (unit NLCD21)
17	Comm/Ind/Trans	commindtrans	%	USGS National Land Cover Database (unit NLCD23)
18	Disturbed High Hazard Lands	disthhl	%	Pct. of watershed in TRPA Land Capability Classes 1-3 (high hazard) that is developed (Cartier *et al.*, 1994)
19	Disturbed Low Hazard Lands	distlhl	%	Pct. of watershed in TRPA Land Capability Classes 4-7 (low hazard) that is developed (Cartier *et al.*, 1994)
20	Percent Impervious	pctimp	%	Minor and Cablk, 2004; modified by Tetratech (Riverson *et al.*, 2006)
21	Percent Turf	pctturf	%	From Tetratech (Riverson *et al.*, 2006; in press)
22	Percent Highway	pcthiway	%	Area of primary roads (highways) as pct of watershed, from Tetratech (Riverson *et al.*, 2006)
23	Non-Highway Pct. Imp.	nonhiwayimp	%	(Pct Impervious)-(Pct Highways)
24	Residential Pct. Imp.	residimp	%	Impervious areas classified as single and multi-family residential, as pct of watershed, from Tetratech (Riverson *et al.*, 2006)
25	Comm/Ind/Util Pct.	cicuimp	%	Luck *et al.*, 2002; Impervious area classified as Commercial/industrial/communication/utilities, as pct. of watershed
26	Dirt Road Density	dirtrd	km/km^2	Luck *et al.*, 2002; Forest Service unpaved roads, Forest Service trails, Calif. Tahoe Conservancy park trails, and Nevada State Parks trails GIS layers
27	Local Roads	usfslocalden	km/km^2	Luck *et al.*, 2002 Forest Service local roads layer

and minimizing the standard error by keeping the number of coefficients small (Helsel and Hirsch, 1995). A Cp greater than $(p + 1)$ indicates that the regression model is overfit, with too many variables; a model with a Cp less than $(p + 1)$ indicates that the regression model is under-fit, possibly leaving out at least one important variable (Mallows, 1973).

In cases where the dependant data were spread over more than one order of magnitude, we took the natural log of the data, and used scatter plots to verify that the regression relationships with the transformed data were more linear than with the untransformed data. Multiple regression models were then fitted to the chosen explanatory variables (EVs).

To verify that we selected a good model, we used various statistical tests. Partial F tests were completed for each explanatory variable to check for their individual significance to the model. An F test was also used to check for significance of the overall model. A full residual diagnosis was completed to check the models for normality, constant variance, outliers, and linearity. The models were checked for multicollinearity in two ways. First, the variance inflation factor was calculated. Second, the correlation coefficients and their corresponding p-values were calculated to examine the linear relationship between all explanatory variable in the model.

To facilitate comparisons of the relative importance of individual explanatory variables, we standardized them before performing the multiple regression analyses (Devore, 2004). The results thus show the relative magnitude of the regression coefficients and bring attention to the more influential variable. The SWM regressions were done with concentrations in mg/l; the LTIMP concentrations were in μg/l for all but SS, which were in mg/l.

TABLE 4. Potential Explanatory Variables Used in the Regression of SWM Data.

No.	Variable	Code	Unit	Source
1	Single Family Residential	SFR	%	Luck *et al.*, 2002
2	Single Family Residential Pervious	SFP	%	Luck *et al.*, 2002; Minor and Cablk, 2004
3	Single Family Residential Impervious	SFI	%	Luck *et al.*, 2002; Minor and Cablk, 2004
4	Multi-Family Residential	MFR	%	Luck *et al.*,2002
5	Multi-Family Residential Pervious	MFP	%	Luck *et al.*, 2002; Minor and Cablk, 2004
6	Multi-Family Residential Impervious	MFI	%	Luck *et al.*, 2002; Minor and Cablk, 2004
7	Pervious Residential	PERVRES	%	Luck *et al.*, 2002; Minor and Cablk, 2004
8	Impervious Residential	IMPRES	%	Luck *et al.*, 2002; Minor and Cablk, 2004
9	Commercial/Industrial/Communications/ Utilities	CICU	%	Luck *et al.*,2002
10	Commercial/Industrial/Communications/ Utilities Pervious (CICU-PERV)	CICU-PERV	%	Luck *et al.*, 2002; Minor and Cablk, 2004
11	Commercial/Industrial/Communications/ Utilities Impervious	CICU-IMP	%	Luck *et al.*, 2002; Minor and Cablk, 2004
12	Primary Roads	P_RDS	%	Luck *et al.*, 2002
13	Secondary Roads	S_RDS	%	Luck *et al.*, 2002
14	Primary and Secondary Roads	(P + S)_RDS	%	Luck *et al.*, 2002
15	Vegetated Area	VEG	%	Luck *et al.*, 2002
16	Slight Erosion Hazard	S	%	Luck *et al.*, 2002 and Rogers, 1974
17	Moderate Erosion Hazard	M	%	Luck *et al.*, 2002 and Rogers, 1974
18	High Erosion Hazard	H	%	Luck *et al.*, 2002 and Rogers, 1974
19	Average Percent Slope	SLOPE	%	Luck *et al.*, 2002 10 m Digital Terrain Model
20	Ave. Annual Precipitation	PRECIP	cm	Mean Annual Precipitation, from PRISM model; (Daly *et al.*, 1994).
21	Percent Impervious Cover	IMP	%	Minor and Cablk, 2004
22	Density of Single Family Residence	D-SFR	Lots/ha	Luck *et al.*, 2002
23	Density of Multi-Family Residence	D-MFR	Lots/ha	Luck *et al.*, 2002
24	Density of Residential Areas	D-RES	Lots/ha	Luck *et al.*, 2002
25	Parent Rock Type	G or V	Qual. variable	Luck *et al.*, 2002 and Rogers, 1974
26	Contributing Area	AREA	ha	Luck *et al.*, 2002

RESULTS

Constituent Concentrations

Figure 4 shows the average SWM constituent concentrations (across all sites) for wet weather flows (snowmelt and frontal rainstorms), compared with summer flows (thunderstorm events), for WY 2003 and 2004. In 2003, a total of 34 thunderstorm events were sampled (one to seven per station), with a total of 332 samples collected. In 2004, only eight thunderstorm events were sampled. The constituent concentrations are all higher, on average, for thunderstorm events than for snowmelt and frontal rainfall runoff. A one-way ANOVA of the 2003 thunderstorm data, along with Tukey's multiple comparison procedure showed limited inter-site differences in EMCs during thunderstorms. The Bonanza Ave.(BB) site had significantly higher concentrations in SS than Regan Beach, South Lake Tahoe Y, and Speedboat Ave. (SB) ($F = 3.64$, with 7 and 26 df; $p < 0.01$) but there were no significant differences between sites for the other constituents.

A comparison of discharge-weighted (Q-wtd.) SWM concentrations (2003-2004) with the discharge-

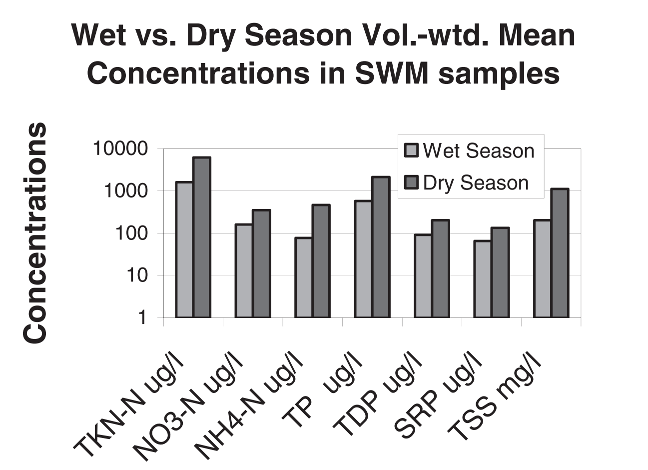

FIGURE 4. Volume-Weighted (Q-Wtd.) Mean Wet-Season and Dry-Season (mostly thunderstorm) Constituent Concentrations in Stormwater Monitoring (SWM) Samples. TKN, total Kjeldahl nitrogen; TP, total phosphorus; SRP, soluble reactive phosphorus (mostly PO_4-P); TSS, total suspended sediment.

weighted LTIMP data is shown in Figures 5a-g. LTIMP stations marked with an asterisk (e.g., WC8*) are downstream stations with the upstream influence

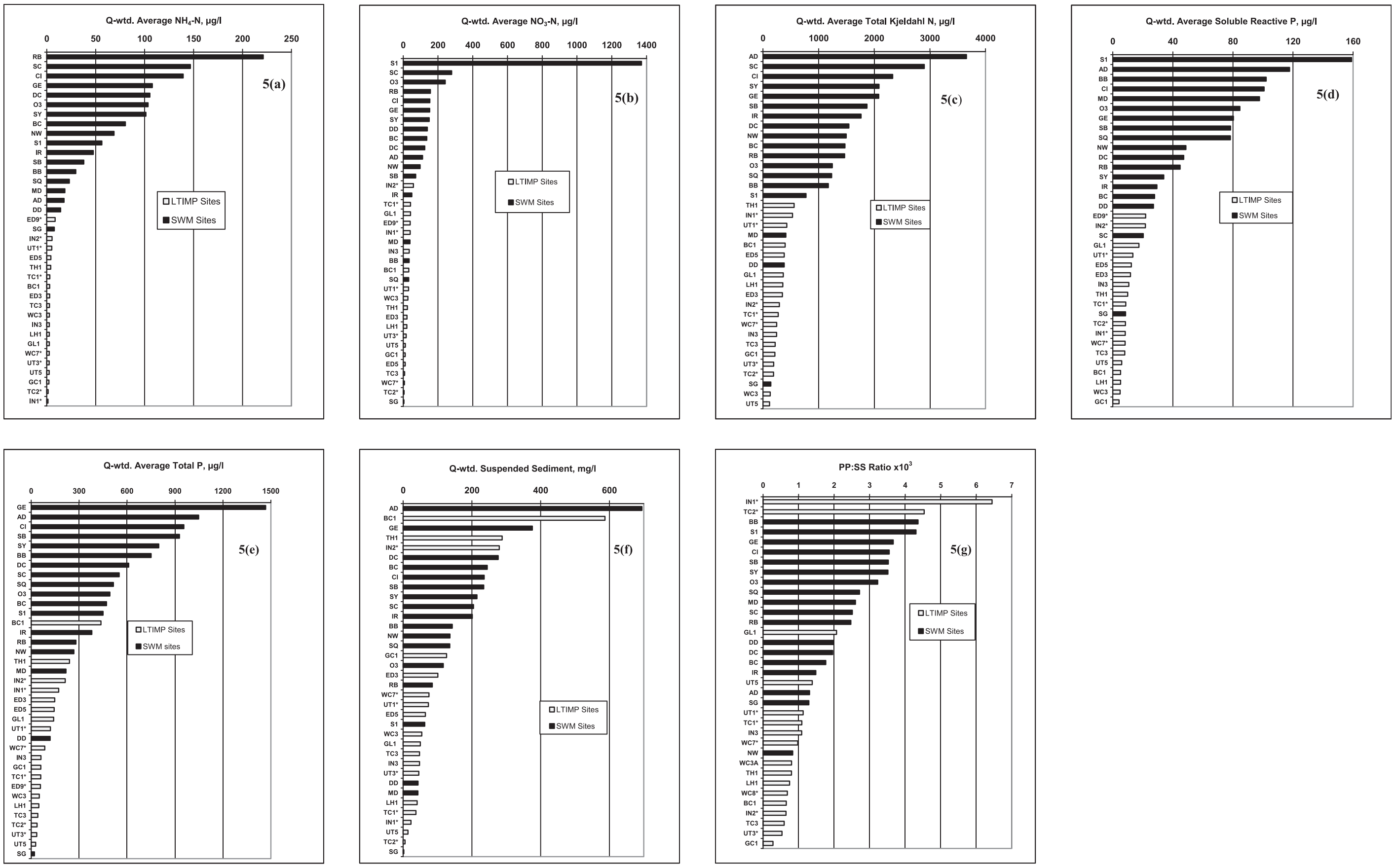

FIGURE 5. (a-g) Volume-Weighted Mean Concentrations (Q-wtd. average) for SWM (2003-2004) and LTIMP (1993-2000) Data.

subtracted (e.g., WC8-WC7), as described above. They generally represent contributing areas with some influence of development. The LTIMP data cover the period 1993-2001, so the two datasets represent different time periods. Nevertheless, the differences between the SWM (representing small urbanized catchments) and the LTIMP data for the larger watersheds are striking. The SWM Shivagiri site is a control site added in WY 2004 in a forested ephemeral stream, and consistently had low concentrations of nitrogen, phosphorus, and SS.

Station WC8* represents a developed alluvial terrace at the lower end of Ward Valley (see Figure 1). The estimated mean concentrations for all constituents were one to two orders of magnitude higher than for the other LTIMP sites. A residential development is separated from Ward Creek by a well-vegetated floodplain and no surface flow-paths for stormwater runoff to the creek are visible. Although inflow of shallow ground-water from abandoned septic tanks or a leaking sanitary sewer line cannot be ruled out, it seems more likely that the apparent high concentrations are an artifact of the effort to resolve relatively small differences between two stations (WC8 and WC7) with relatively high discharges and total loads. For the statistical analysis of the LTIMP data, the area between WC7 and WC8 was considered an outlier, and was not included. It is included in Figure 5 because the concentrations fall within the ranges in the SWM dataset, although the validity of the Q-wtd. concentration data are questionable.

In the LTIMP streams, Particulate P (PP) averaged 86% of TP, ranging from 58 to 96% (Hatch *et al.*, 2001). At the SWM sites, PP accounted for 74% of the TP, and ranged from 51 to 94%. These figures provide a basis for comparing PP with SS. Figure 5g shows the ratio of Q-wtd. PP to Q-wtd. SS. The two stations with the highest ratios represent downstream contributing areas in Incline Creek (IN1*) and Trout Creek (TC2*). Both of these areas had unusually low Q-wtd. mean SS concentrations, and both have significant developed areas. By and large, the SWM sites had higher ratios of PP:SS, suggesting that SS from developed areas is enriched in P compared with the less-developed larger watersheds. The enrichment could result from of a relatively greater contribution of surface soil erosion to the SS load from developed areas.

Multiple Regression of Concentrations vs. Catchment Characteristics

The regression coefficients and corresponding measures of error for the SWM data are shown in Table 5. A satisfactory regression model for Q-wtd mean TP concentration was not found, but we did find univariate models relating Total Dissolved P (TDP) and ln(SRP) to percent impervious area, with $R^2 = 0.43$ and 0.47, respectively. The strongest relationship (highest R^2 value) was found for the Q-wtd mean concentrations of ammonium-N.

Table 6 shows the regression results for Q-wtd. mean concentrations in the LTIMP streams, for nitrate-N, TKN, ln(TP), and ln(SRP). Ammonium-N was below the MDL in most of the samples, and dropped from the statistical analysis, and the SS regression was undermined by collinearity problems. Also, the method used to remove the influence of upstream stations from downstream stations assumes that the constituent concentrations are conservative between stations within a three-hour period, that is, there are no sources (other than inflow) or sinks between stations. For SS, transport (and concentration) may change rapidly as discharge rises and falls, especially during storm runoff and snowmelt (Leonard *et al.*, 1979). Material can be deposited between stations as discharge falls, or be mobilized as discharge increases (e.g., stream channel erosion, Simon *et al.*, 2003). In this case, the water sampled at an upstream station is not the same water sampled at the downstream station. Even if it were, SS could be entrained or deposited between stations during the time interval between sample collections. In contrast, dissolved constituents would mostly stay in solution during transport between the two sites.

TABLE 5. Regression Results of SWM Q-wtd. Concentrations (mg/l) *vs.* Catchment Characteristics.

	LN NH_4-N	NO_3-N	TKN	LN SRP	TDP
n	19	18	17	19	19
R^2	0.62	0.52	0.47	0.47	0.43
R^2 adj	0.58	0.46	0.39	0.47	0.43
p	<0.0004	<0.0041	<0.0122	<0.0012	<0.0021
Intercept	−2.92	0.12	1.53	−2.90	0.10
Residential Pct. Impervious				0.49	0.03
Pct. Impervious		0.04			
Density of Multi-Family Residential Lots	0.34	0.03	0.30		
Average Slope	−0.56		−0.29		

Notes: All explanatory variables were standardized prior to performing the regression. Partial F-test for all coefficients had a $p < 0.05$.

TABLE 6. Regression Results for Discharge-Weighted Mean Concentrations (μg/l) *vs.* Watershed Characteristics, for LTIMP Watersheds.

	NO_3-N	TKN	LN TP	LN SRP
n	19	19	19	18
R^2	0.40	0.37	0.42	0.74
R^2 adj	0.32	0.29	0.34	0.70
p	<0.0168	<0.025	<0.014	<0.0001
Intercept	25.79	294	4.45	2.21
Watershed Area				−0.26
Mean Ann. Precip.				−0.35
Riparian Rivers, pct.		−49	−0.32	
Pct. Impervious	8.03	59		
Dirt Rd. Density × Mean Ann. Precip.	−5.64			
Dirt Road Density			0.46	

Notes: All explanatory variables were standardized prior to performing the regression. Partial F-test for all coefficients had a $p < 0.1$.

Constituent Loads

Although runoff at the SWM sites from summer thunderstorms is on average considerably more concentrated in nitrogen, phosphorus, and sediment than wet-season runoff, the higher concentrations may not result in higher thunderstorm loads, since the annual runoff volume during snowmelt and frontal storms is usually much higher than during thunderstorms. Figures 6a and b compare the dry-season (mostly thunderstorm) and wet-season loads for 2003, for nitrate-N and TSS, for stations at which thunderstorms were sampled that year (stations were added in the second year, but virtually no thunderstorms occurred). Patterns for the other constituent are similar; that is, at about half of the stations, and for different constituents at the stations, the thunderstorm loads exceeded the wet-weather loads. The sporadic nature of thunderstorm distribution (in both space and time), and lack of summer thunderstorms in 2004 make generalizations difficult, except to say that summer thunderstorms sometimes play an important role in generating nitrogen, phosphorus and SS loads in urban runoff in the Tahoe basin.

Figures 7a-c show the average annual constituent yields (load per unit area) for the main LTIMP watershed stations (at tributary mouths), averaged over WYs 1990-1901. The nitrate-N yields shown are somewhat higher than values previously reported (Coats and Goldman, 2001), since the calculation of loads in this study adjusted for a chemical interference in the determination of nitrate-N concentrations. The nitrate-N loads reported by Coats and Goldman (2001) should be adjusted upward by an average of

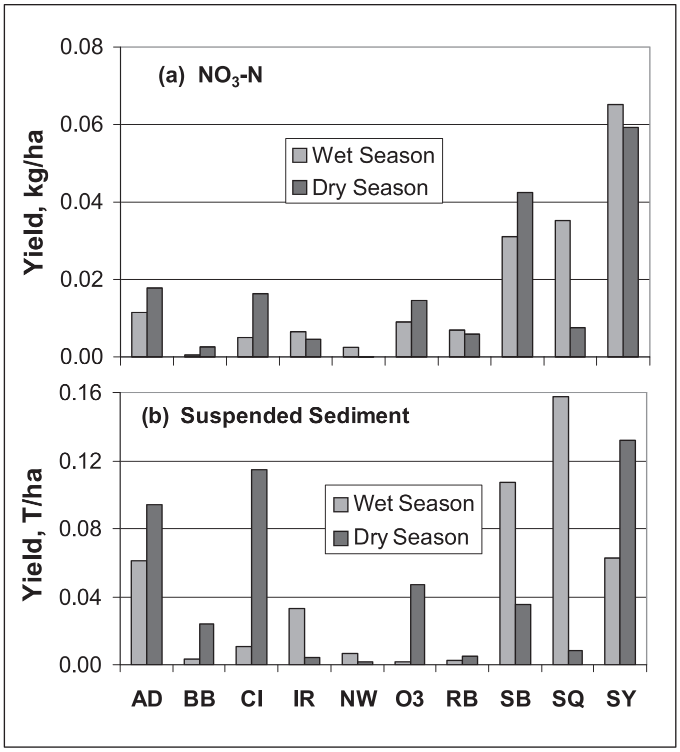

FIGURE 6. Wet-Season and Dry-Season Nitrate-N and Total Suspended Sediment Yields, 2003, at SWM Sites. Dry-season rainfall is mostly from thunderstorms, very few of which occurred in 2004. The patterns for ammonium-N, TKN, SRP, and TP show similar variability. At some sites, summer thunderstorms contributed significantly to total loads.

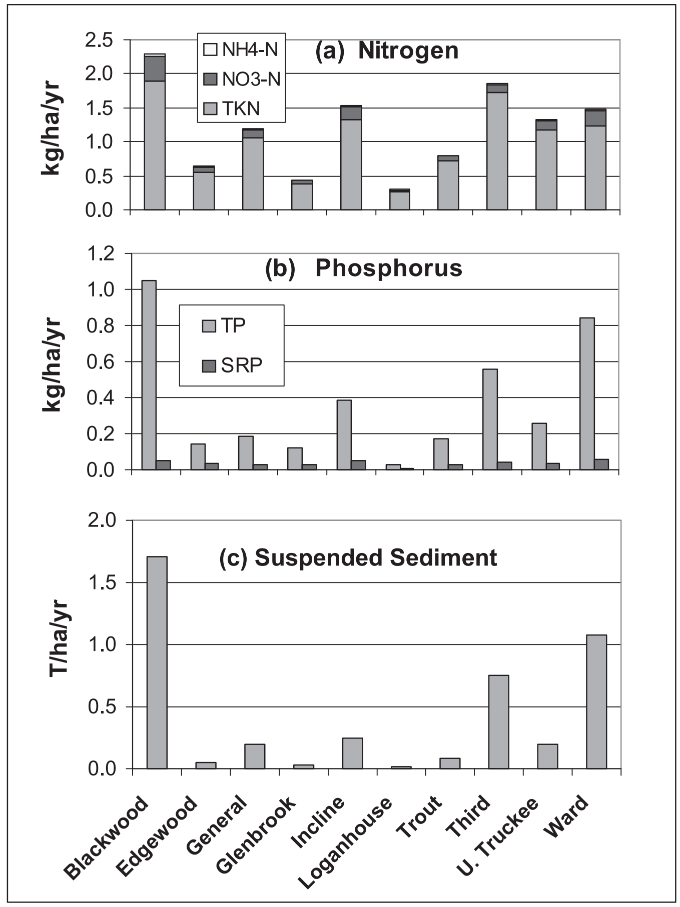

FIGURE 7. Average Annual Yields of Nitrogen and Phosphorus for the Main LTIMP Watershed Stations (at basin mouths), Averaged Over Water Years 1990-2001.

54%. Note that the nitrogen contribution from the LTIMP watersheds is dominated by organic nitrogen. Only about 15% is oxidized nitrogen, and an insignificant fraction is ammonium-N.

The LTIMP watershed yields for TP and SRP are shown in Figure 7b. Figure 7c shows the SS yields. As with nitrogen, the most readily available form of phosphorus (SRP) makes a relatively small contribution to the total P. However, particulate-P bound to sediments in Tahoe streams does have a bioavailable component that can be released in the lake's water column (Ferguson, 2005). Note also that the west-side basins (Ward and Blackwood Creeks) are relatively heavy contributors of both TP and SS per unit area.

In Figure 8, the annual runoff is shown, for the 10 LTIMP basins, and in Figure 9, the constituent yields (load per unit area) are shown. The effect on SS and TP of the flood of January 1, 1997, is readily apparent. This flood resulted from a heavy rain-on-snow event with a recurrence interval that varied from <5 to >100 years at gaged tributaries in the Tahoe basin (Rowe *et al.*, 1998). In Ward and Blackwood Creeks the flood peak was (respectively) 13% less than and 32% greater than the estimated 100-years peak discharge (Crompton *et al.*, 2002), and it triggered large stream-side landslides and major channel changes. WY 1995 actually had higher runoff than 1997, and this is reflected in the annual yields of the dissolved

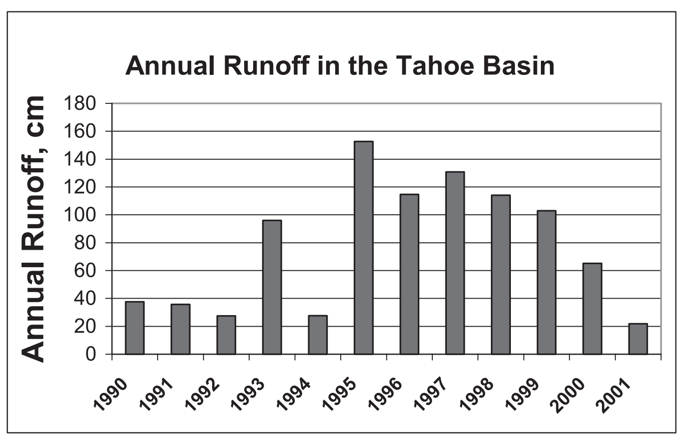

FIGURE 8. Average Annual Runoff for the Main LTIMP Stations (at basin mouths), Averaged Over the 10 Primary Watersheds.

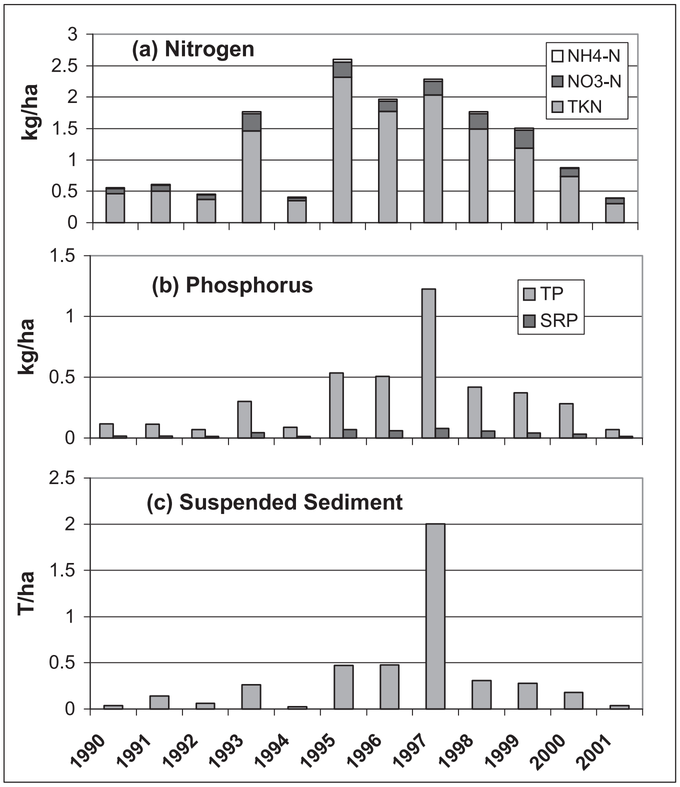

FIGURE 9. Average Nitrogen and Phosphorus Yields at the Main LTIMP Stations, Averaged Over the 10 Primary Watersheds.

constituent, and TKN. In contrast, the years of 1990-1992, 1994, and 2001 were relatively dry, and total loads of all constituents were low. Similarly, a landslide during the late 1980s in the watershed of Third Creek greatly increased the SS load of that creek through WY 1993 (Tim Rowe, USGS, *personal communication*). It is tempting to discard the data from such "unusual" events, and thus reduce the SS variance for regression analysis. But floods, landslides and droughts are an important part of the long-term sediment "picture," and cannot be discounted.

Multiple Regression of Yields vs. Catchment Characteristics

Table 7 shows the results for the regressions of constituent yields *vs.* watershed characteristics, for the LTIMP watersheds. For nitrate-N, TKN, SRP, and TP and ln(SS) models were found that explained 45-72% of the variance in total yield. For SS the best model only explained 57% of the variance, with two explanatory variables: MAP and local roads. Both coefficients were positive. The inclusion of MAP does not add much information, since MAP drives discharge, and load is the product of concentration and discharge.

TABLE 7. Regression Results for Watershed Yields *vs.* Watershed Characteristics, for LTIMP Watersheds

	NO_3-N	TKN	SRP	TP	LN SS
n	19	19	19	18	19
R^2	0.45	0.47	0.60	0.72	0.57
R^2 adj	0.34	na	0.49	0.66	0.52
p	<0.0266	<0.001	<0.008	<0.0004	<0.001
Intercept	0.125	1.024	0.041	0.275	−1.962
Watershed Area			−0.013		
Mean Ann. Precip.					1.013
Alluvial Rivers Pct.			0.010		
Soil Index	−0.043		−0.014	−0.061	
Local Roads			0.010		0.580
Percent Volcanic	0.045				
Percent Impervious	0.04			0.118	
Percent Granitic		−0.370		−0.098	

Notes: All explanatory variables were standardized prior to performing the regression. SS is in tonnes/ha/years; N and P are in kg/ha/years. Partial F-test for all coefficients had a $p < 0.1$.

Sediment budget studies and sediment transport models have identified stream channel erosion in the Tahoe basin as a major source of SS load (Hill *et al.*, 1990; Nolan and Hill, 1991; Simon *et al.*, 2003). The finding that Local Roads are a significant contributor to SS is consistent with the contribution of channel erosion to sediment yields, since road networks may increase downstream peak runoff and contribute to channel erosion. For the LTIMP watersheds, geomorphic and sediment transport models (Simon *et al.*, 2003) will likely contribute more to an understanding of SS sources than the GIS-based regression approach.

DISCUSSION AND CONCLUSIONS

Although there have been few efforts in urbanizing subalpine watersheds to relate water quality to watershed characteristics, there have been numerous efforts in other regions and landscape types to develop such relationships, at various spatial scales. These have been most successful where watersheds have spanned a broad range in land use, including urbanized, agricultural, and forest lands (Herlihy *et al.*, 1998; Groffman *et al.*, 2004). Where soil fertility, land use and mean annual discharge are confounded, interpreting results becomes difficult (Hill, 1978). Step-wise multiple regression using large numbers of explanatory variables along with their logs, reciprocals, and squares has been successful in explaining 80-90% of the variance in N and P export in some cases (Dillon *et al.*, 1991) but the physical interpretation of the results is problematic. More parsimonious models that seek to maximize goodness of fit with a minimum number of variables, however, have been able to explain 76 and 78% of dissolved organic carbon and TP export from forested catchments (Dillon and Molot, 1997). Caraco *et al.* (2003) found that relationships between nitrate-N export and watershed characteristics (especially human population density) vary across spatial scales, with weaker relationships for basins <100 km^2. The development and wide dissemination of GIS databases together with DEMs has facilitated analysis of not just land use/land cover variables, but also hydrologic, hydraulic and topographic variables (Soranno *et al.*, 1996; Basnyat *et al.*, 2000; Sliva and Williams, 2001) as well as use of complex landscape metrics (Jones *et al.*, 2001).

In analyzing statistical relationships between water quality and watershed characteristics, some precautionary principles must be kept in mind. First, it cannot be assumed that the suite of independent variables under consideration includes all of the important variables that may be influencing water quality. For example, it is known that Blackwood Canyon has a long history of logging, overgrazing and gravel mining from the 1870s until the mid-1960s. This land use history is not well characterized by current GIS features, except perhaps in terms of unimproved dirt roads, so a specific variable that would address these historic impacts is not included in the statistical analysis.

Second, with many somewhat-correlated explanatory variables to choose from, there are usually several possible combinations of variables that give almost equally satisfactory results. That a given variable is not included in the final model does not indicate that it has no effect on a given constituent. For example, "percent impervious surface" is broken down by land use category, and the categories (residential, commercial/industrial, etc.) are often correlated, so the inclusion of both in a regression model may cause it to become unstable, as indicated by a high variance inflation factor. The choice of the final set of independent variables requires a certain amount of judgment about ecological processes as well as statistics.

A third (and related) *caveat* is that "correlation does not prove causation." A good example of this may be seen in the inclusion of "highway percent impervious surface" with a highly significant negative coefficient in some of the candidate models. It is highly unlikely that highways in the basin are removing nitrate, phosphorus, and sediment from runoff. Rather, the watersheds on the west side of the basin (Blackwood, Ward, and General Creeks) have relatively high constituent loads because they have high total annual discharge, compared with many of the other watersheds. Since load is a product of concentration and discharge, these basins have relatively high yields of nitrate-N, TP, and SS. However, they are not transected by highways, whereas some of the drier east-side watersheds (with lower loads) are crossed by a four-lane highway, so there is an apparent negative relationship between highways and constituent loads.

With these limitations in mind, it is possible to use the results for both the LTIMP and SWM data analysis to formulate hypotheses about the factors that influence constituent concentrations and loads.

Looking at the final LTIMP and SWM models for all constituents, several patterns emerge. First, for three variables – nitrate-N, SRP and TP – there is a negative relationship between soil index and nutrient and sediment. Soil index was derived from forest site index, that is, the height of a co-dominant tree at 100 years. High values of this index are indicative of well-developed soils with good moisture holding capacity and high fertility; low values are characteristic of thin, rocky, and poorly developed soils. One would expect that the more productive and better-developed ecosystems would have tighter nutrient cycling mechanisms, and be less "leaky" than the poorly developed ecosystems. In a study of streamwater nitrogen yields in the central Sierra and Rocky Mountains, Sickman *et al.* (2002) found a negative relationship between the natural logarithm of soil cover (as percent of watershed area) and dissolved inorganic nitrogen (DIN) yields, with R^2 of 0.82 for Sierra streams, and 0.91 for Rocky Mountain streams. This Tahoe basin study found that a linear model generally worked best for nitrate-N, SRP, and TP, but the results reported here are consistent with their findings. They are also consistent with the results of Brown *et al.* (1973) for streams in and near the Tahoe basin.

However, to some extent, soil development and MAP in the Tahoe basin are confounded. Poorly developed soils are characteristic of both high elevation areas with high MAP on the west side of the basin, and drier areas on the east side of the basin (see Figure 2). The Pierson correlation coefficient (r) between MAP and Soil Index was −0.54. Since water discharge is highly correlated with MAP, and load is the product of concentration and discharge, soil index may in part be a surrogate for MAP. Nevertheless, Soil Index was consistently a more useful variable than MAP in explaining the variance in total yields.

In a recent study at two sites in the Tahoe basin, Miller *et al.* (2005) found that interflow in the litter layer above a hydrophobic layer contains concentrations of DIN and SRP about three orders of magnitude higher than soil water, and far higher than any concentrations previously reported in the Basin.

Previous studies in the Tahoe basin have shown that well-developed soils with a thick layer of litter and humus are extremely efficient in scavenging DIN from snowmelt water and that dissolved organic nitrogen released from the forest floor is effectively removed as snowmelt water percolates through a well-developed soil (Coats *et al.*, 1976). Clearly the hydrologic flow-paths that water follows from hillslopes to the stream have a major bearing on localized streamwater concentrations and constituent loads.

A second general observation is the importance of land use variables, especially multi-family residential density and impervious surface cover in the SWM data (Table 5). And land use may explain the apparently anomalous finding that ammonium-N and TKN concentrations are negatively related to slope. Developed parcels in the steepest subdivisions (such as Dale Drive and Mountain Drive) are situated on mountainsides, often have spectacular views of the lake, and command very high prices. Gardens are well irrigated and carefully tended, and roadside gutters are armored with carefully placed rock. Recommendations of the Backyard Conservation Program of the Tahoe Resource Conservation District (http://tahoercd.org/bc.php) are commonly implemented. In contrast, yards in the lower-priced subdivisions (e.g., Osgood and Coon St.) on flatter ground near the lake often do not have well-tended landscaping. The soils are churned and sometimes compacted by vehicles parked in the yards and by heavy foot traffic. Understory vegetation and a litter/humus layer on the soil are absent, and roadside gutters are often unarmored. It would thus be reasonable for stormwater and snowmelt runoff from the flatter ground to produce higher concentrations of ammonium and TKN. The negative relationship between slope and water quality has been found in other regions. In a recent study of 17 streams along a forest-urban gradient in the Seattle area, Brett *et al.* (2005) found a negative relationship between P concentration and slope, which they attributed to the higher density of development on flatter ground.

Land use variables also entered the equations for the LTIMP watershed. Percent impervious surface, U.S. Forest Service (USFS) local road density, and dirt road density all played a role in one or more of the equations for concentration or yields. Curiously the nitrate-N yield equation includes a negative coefficient for the dirt road × precipitation interaction term. This probably reflects some peculiarity in the distribution of dirt roads in the low *vs.* high precipitation zones of the basin.

Brett *et al.* (2005) found that in the Seattle area streams, P concentration was moderately correlated and nitrogen concentration was slightly correlated with urban development. In contrast with Tahoe basin streams, nitrate-N rather than TKN was the dominant form of nitrogen in Seattle area streams, possibly due to the influence of red alder. The presence of localized natural sources of nitrate in both Tahoe Basin and Seattle area streams may explain the difficulty of finding strong relationships between nitrate-N and land use.

The primary metrics of land use identified in this study – impervious surface, lot density and road density – may act in several ways to influence water quality and constituent yields. Increased stormwater runoff from impervious surfaces exacerbates downstream soil and channel erosion. Impervious surfaces intercept atmospheric deposition of nitrogen, phosphorus, and dust, and "short-circuit" the distributed hydrologic flow-paths through the soil that would otherwise remove these substances from runoff. But to a large extent, anthropogenic impervious surface may simply be a surrogate for many different sources and processes that contribute to nutrient and sediment loads. These may include (1) vehicle emissions of ammonium and nitrogen oxides as combustion products (Durbin *et al.*, 2001); (2) phosphorus from crankcase oil (Kaleli, 2001); (3) traction sand applied to roads and highways, which is ultimately pulverized to silt-sized material (Gertler *et al.*, 2006; (4) waste from dogs, estimated to generate annually about 12 tonnes of total N and 3 tonnes of total P in the basin (Schuster and Grismer, 2004); (5) fertilizer applied to lawns and golf courses (Nagy, 2003); (6) accelerated decomposition of the forest floor in residential areas due to foot and vehicle traffic; and (7) road-side ditches that are unprotected by curb and gutter.

A third pattern that emerges is the role of geologic and geomorphic variables in modifying water quality and yields in the LTIMP watersheds. Nitrate-N yields were positively related to areas of volcanic bedrock. In these areas, impermeable layers of tuff (cemented volcanic ash) create springs that support nitrogen-fixing mountain alder, which fixes atmospheric nitrogen and locally contributes to streamwater nitrate-N concentrations and loads. The negative coefficients for Percent Riparian Rivers, for TKN and ln(TP) is consistent with a role for riparian vegetation in maintaining water quality. And the negative relationship between watershed area and SRP yield in the LTIMP data could be related to differences in nutrient uptake length for SRP between small and large watersheds (Mulholland *et al.*, 1997).

The results of this study have helped to inform the development of a combined hydrologic-water quality model that is being used to help determine TMDL allocations for the Tahoe basin (Shen *et al.*, 2005; Riverson *et al.*, 2006; see also http://www.epa.gov/athens/wwqtsc/html/lspc.html). But the ultimate test of water quality research in the Tahoe basin will be its utility in arresting the decline in the Lake's clarity. That will depend in large part on the will and commitment of public and private land owners, and of political leaders and regulators at the local, state, and federal levels.

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