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STREAM PHOSPHORUS TRANSPORT IN THE LAKE TAHOE BASIN, 1989–1996

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Abstract. Lake Tahoe is undergoing the initial stages of cultural eutrophication due to human alteration of the airshed and watershed. The lake's switch from nitrogen (N) to phosphorus (P) limitation has been attributed primarily to atmospheric N loading. This places an increased importance on controlling watershed movement of P to the lake. A stream water quality monitoring data set consisting of nine streams in the Lake Tahoe basin has been analyzed to characterize the spatiotemporal variation of P delivery to the lake. This data is from the Lake Tahoe Interagency Monitoring Program (LTIMP), which provides scientific data for planning and regulatory agencies to address environmental problems in the Lake Tahoe basin. Results indicate that P delivery (concentrations, loads) varies greatly at interannual, seasonal, and spatial scales. Annual and seasonal total P (TP) concentrations can vary up to three orders of magnitude in a given stream and are strongly associated with suspended sediment. Particulate P is the major form of P transported by Tahoe streams and was strongly correlated with percent surficial geologic deposits, which are primarily located near streams. Tahoe streams with the highest annual P concentrations often had the lowest annual P loads, and visa versa. P loading is greatest during the spring snowmelt (75% of annual average). Potential watershed parameters influencing P delivery to Lake Tahoe have been identified as precipitation, basin area, basin steepness, and road and human development coverage. Results also suggest that human development impacts on stream P loads are most prevalent during high precipitation years. Identification and quantification of stream sediment and P sources such as streambanks and impervious surface is necessary to aid in watershed restoration efforts.

Keywords: Lake Tahoe, phosphorus, streams, water quality, watershed characteristics

1. Introduction

Arguably the greatest change to Lake Tahoe in the last four decades has been the enhanced transport of sediment from the watershed, the steady increase in primary productivity, and the loss of about 30 cm of transparency each year since measurements began in 1968 (Goldman, 1988; Jassby *et al.*, 1999). While nitrogen (N) was the primary limiting nutrient to the lake's algal population prior to the 1980s, atmospheric deposition of N directly onto the lake surface has led to a shift towards increasing phosphorus (P) stimulation (Goldman *et al.*, 1993; Jassby *et al.*, 1994, 1995).

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An estimated total P budget for Lake Tahoe has been developed (Reuter *et al.*, 1998). Atmospheric deposition accounted for 9.7 metric tonnes (MT) or approximately 25% with direct loading from the watershed contributing 27.4 MT (64%). Nearly equal contributions came from a combination of the lake's 63 tributaries and direct runoff to the lake. There is a concern that human development and activities in the basin enhance erosion, surface flow, and consequently stream P loading to the lake. The modern history of watershed activities at Lake Tahoe bagan after 1870 when most of the basin was heavily logged to build mineshafts in western Nevada (Heyvaert, 1998). The forest recovered by the early 1900s, and the basin remained largely undeveloped until the 1960 Winter Olympic Games at nearby Squaw Valley, CA. Since then, human development and impacts from the resident and tourist populations have increased, significantly enhancing environmental degradation in the region. Impacts include lake eutrophication, soil erosion, air pollution, wetland destruction, decline of forest health, and a loss of biodiversity.

In 1971 the Tahoe Regional Planning Agency (TRPA) was established by Congress to manage the human and environmental resources in the Tahoe basin. Since that time, the entire basin has been sewered with the treated sewage pumped out of the basin. A program to purchase environmentally-sensitive land has been established, strict permitting conditions have been adopted, and many restoration projects using best management practices have been implemented. Industrial and agricultural sources of P in the basin are essentially non-existent. The TRPA has established environmental thresholds for air, stream, lake, and runoff quality as targets for management efforts. Efforts to achieve water quality thresholds are addressed in part by placing a limit on human development activities that create impermeable coverage. This policy is intended to allow rain and snowmelt water to infiltrate into the ground thereby reducing surface erosion and the transport of sediment and nutrients to the streams and eventually the lake.

The Lake Tahoe Interagency Monitoring Program (LTIMP) was developed in 1979 to provide scientific data for planning and regulatory agencies to address environmental problems in the basin. In addition to atmospheric and lake monitoring, sites to monitor discharge and water quality parameters were established on ten streams representative of conditions basin-wide. Sixteen years of data now exist for some LTIMP streams, although certain streams did not enter the program until the late 1980s. The LTIMP stream data set is consistent from WY89 to WY96 (a water year [WY] extends from October 1st to September 30th of the said water year) for the nine streams examined in this study. The objectives of this study were to characterize the LTIMP stream P data set and examine the influence of watershed geomorphology, geology, and indices of human development on stream P delivery to the lake. These analyses will help us understand the variability of stream P delivery to Lake Tahoe at different spatial and temporal scales. Identifying watershed characteristics that are potentially influencing P delivery is important to the future management of Tahoe basin resources.

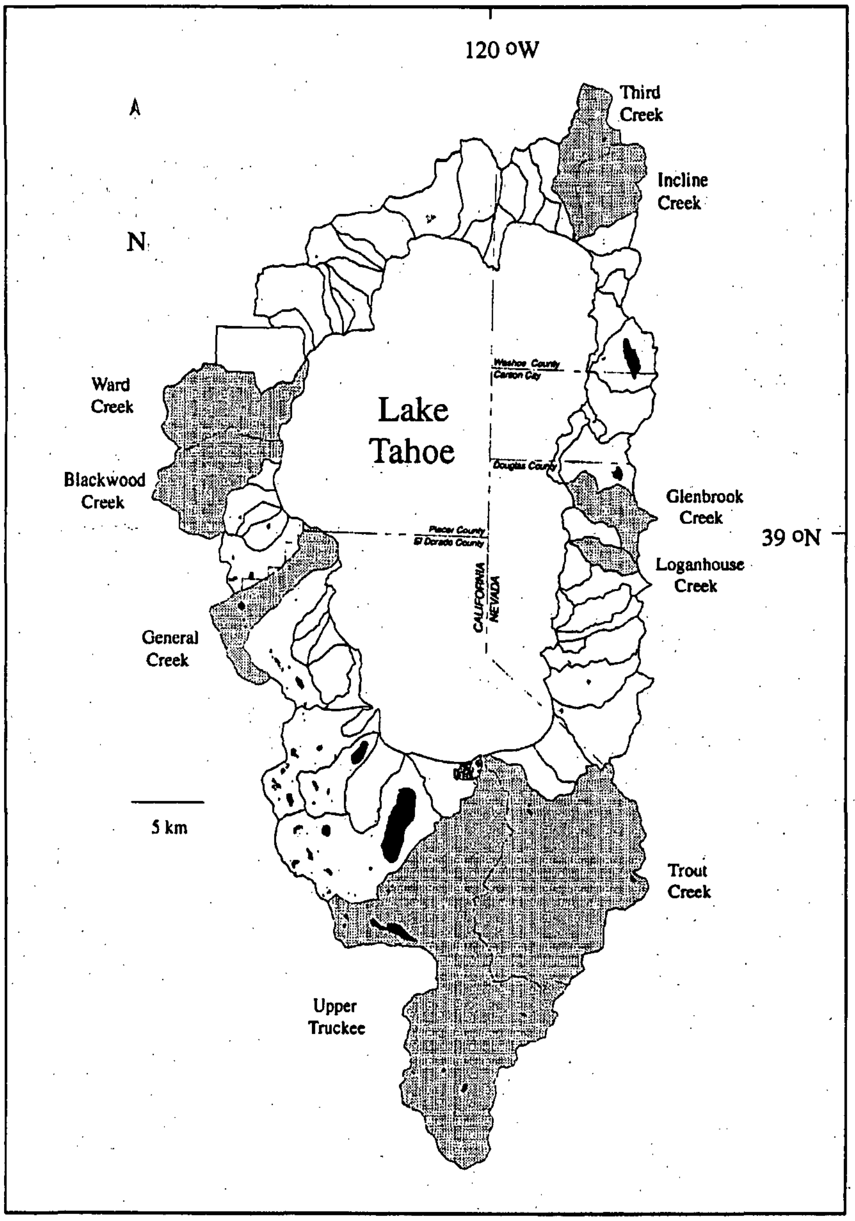

Figure 1. The Lake Tahoe Basin, California-Nevada, U.S.A. Streams for the present study are highlighted. Map courtesy of the Tahoe Regional Planning Agency (Zephyr Cove, NV).

2. Methods

2.1. Description of the Lake Tahoe Ecosystem

Lake Tahoe is an ultra-oligotrophic lake located at the crest of the Sierra-Nevada range (Figure 1). Two-thirds of the lake is located in California, with the remainder in Nevada. The lake has a surface elevation of 1898 m above sea level, a mean depth of 313 m, and a maximum depth of 501 m (Goldman, 1974). Lake Tahoe's large volume of 156 km^3 and its relatively small watershed are largely responsible for the lake's 770 yr hydraulic retention time. Lake Tahoe's drainage and surface areas are 800 km^2 and 500 km^2, respectively.

The lake was formed by graben faulting approximately 3 million years ago, followed by volcanic activity sealing off the north end (Matthews and Burnett, 1971). Slopes rise quickly from the lake shore, reaching 30–50% in many places. Soils are generally granitic, with volcanic soils located mainly in the north and northwestern parts of the basin (Matthews and Burnett, 1971; Goldman, 1974). Soils near the lake consist of alluvial wash deposits. Glaciation occurred prediminantly in the western canyons and high-elevation bowls approximately 11,000 yr ago. The basin is moderately-to-densely vegetated, consisting of mixed fir (*Abies* spp.) and pure pine (*Pinus* spp.) stands. The understory is primarily manzanita (*Arctostaphylos* spp.), huckleberry (*Gaylussacia* spp.), oak *Quercus* spp.), and quaking aspen (*Populus tremuloides*). Current vegetation is mainly secondary and tertiary growth, recovering from intensive logging operations during the late 19th century.

The nine streams within the Lake Tahoe basin that have extensive water quality monitoring data vary with respect to their geomorphic, geological, and urban characteristics (Table I). Geomorphic variables (Hill and Nolan, 1990; TRPA, 1996) are related to watershed topography and location. Erosion hazards were determined from the Bailey (1974) land capability classification, which attempted to determine erosion potential in the Tahoe basin based on soil type and geomorphic setting. Geologic variables are represented by the percentage of each watershed underlain by the following rock types: metamorphic, volcanic, decomposed granite, glaciated granite, and surficial deposits (Hill and Nolan, 1999). Urban variables measure indices of human development. In addition in total road kilometers and road density (Hill and Nolan, 1990), physical coverages of roads and non-road areas were examined (TRPA, 1996). Road coverage included all road types in the basin (paved, unpaved, forest). Development coverage measures both hard (e.g., structures and paved areas) and soft (e.g., dirt areas compacted to the point that water infiltration is negligible) coverage. Examples include commercial/public service areas, recreation areas, and residential areas.

A map of annual isohyetal precipitation values has been development using 46 precipitation stations which had from one to over 80 yr of data (TRPA, 1982). The isohyetal precipitation map is accurate on an annual time scale. Marjanovic (1989) used the isohyetal map in concert with the basin watershed map to calculate mean

TABLE I

Geomorphic, geologic, and urban parameters for LTIMP streams

Station	USGS Gauge	Drainage Area (ha)	Relative Precip. Percentage	Main Channel Length (km)	Main Channel Gradient (km km^{-1})	Drainage Density km km^{-1})	Ground Slope (degrees)	Basin Aspect (degrees)	Elong-ation Ratio	Relief Ratio	Percent High Hazard Land
BLK	10336660	2896	1.85	9.98	0.047	14.17	17.8	55	0.79	0.072	59.3
GEN	10336645	1958	1.80	14.76	0.035	7.89	12.2	45	0.53	0.060	42.3
GLB	10336730	1059	0.91	6.31	0.079	1.44	6.4	270	0.69	0.139	90.5
INC	10336700	1751	1.05	7.50	0.083	1.12	6.3	170	0.68	0.131	90.4
LGN	10336740	565	0.86	5.31	0.140	11.43	15.0	292	0.54	0.170	100.0
THD	10336698	1570	1.31	11.35	0.092	11.75	16.8	180	0.68	0.130	53.0
TRT	10336790	10611	0.98	19.63	0.035	7.89	14.0	337	0.70	0.071	69.3
UTR	10336610	14670	1.29	34.52	0.026	7.08	12.1	0	0.51	0.042	66.7
WRD	10336676	2523	1.79	9.49	0.050	14.01	5.1	22	0.72	0.079	48.8

TABLE I
Continued

Station	Percent Moderate Hazard Land	Percent Low Hazard Land	Percent Meta-morphic Rock	Percent Volcanic Rock	Percent Decomp-osed Granite Rock	Percent Glaciated Granite Rock	Percent Surficial Deposit Rock	Total Roads (km)	Road Density (km km^{-2})	Road Coverage (ha)	Develop-ment Coverage (ha)
BLK	37.4	3.3	10.4	50.2	0.0	0.0	39.4	32.8	1.12	236	13
GEN	57.7	0.0	0.0	0.0	0.0	65.0	35.0	12.9	0.69	229	69
GLB	8.1	1.4	19.3	31.6	44.5	0.0	4.7	24.2	2.29	106	29
INC	4.6	5.0	0.0	21.6	67.4	11.0	0.0	56.0	3.20	167	99
LGN	0.0	0.0	30.9	0.0	69.1	0.0	0.0	4.7	0.81	6	5
THD	35.0	12.0	0.0	7.0	25.8	10.7	56.5	19.3	1.25	72	104
TRT	24.1	6.6	0.0	0.3	64.3	5.0	30.4	70.7	0.75	970	230
UTR	30.7	2.6	0.3	8.9	20.1	24.2	45.5	117.5	0.81	1888	616
WRD	48.8	2.4	1.1	47.9	0.0	0.0	51.0	33.3	1.31	197	259

Relative precip. percentage = (watershed precipitation)/(Tahoe City station precipitation). Geomorphic, land hazard, and rock parameters from Hill and Nolan (1990) except for GLB and INC which were measured from 1:24000 topographic maps, land use maps (Bailey, 1974), and geology maps (Matthews and Burnett, 1971). Coverage parameters from TRPA (1996). BLK = Blackwood Creek, GEN = General Creek, GLB = Glenbrook Creek, INC = Incline Creek, LGN = Loganhouse Creek, THD = Third Creek, TRT = Trout Creek, UTR = Upper Truckee River, WRD = Ward Creek.

annual precipitation for each of the 63 individual watersheds. Dividing these values for each of the LTIMP watersheds by the Tahoe City precipitation station's mean annual value of 70 cm yr^{-1} (from the isohyetal map) results in an estimated relative precipitation (Table I).

2.2. Lake Tahoe Interagency Monitoring Program

The LTIMP follows precise procedures for sample collection, handling, analysis, and quality assurance/quality control (Hunter *et al.*, 1993; Goldman, 1993). Internal quality control procedures for the LTIMP consist of biannual performance audits, system audits, and reports (Hunter, 1996). External quality control procedures consist of analyzing biannual reference samples from the U.S. Geological Survey (Farrar and Long, 1996).

Sampling (30 to 50 per site per year) is intensive during rain-on-soil, rain-on-snow, and temperaure-driven snowmelt events, with less frequent sampling during baseflow conditions. Samples for dissolved P analyses (SRP: soluble reactive P; TDP:total dissolved P) are filtered on site through 0.45 μm membranes. Quarterly field blanks and annual field duplicates are also collected. Samples are stored in the field and laboratory at 4 °C until analysis. Stream discharges were measured by continuous-recording U.S. Geological Survey gauges at 15-minute intervals and also by the technician at the time of sampling.

Soluble reactive P is assayed colorimetrically (within 10 days of sample collection) by the ascorbic acid method (Murphy and Riley, 1962) using a 10 cm pathlength cell. Samples for TDP and TP undergo persulfate digestion (within 30 days of sample collection) prior to color development (Menzel and Corwin, 1965). Total suspended solids (TSS) samples were analyzed gravimetrically (Guy, 1969) at the U.S. Geological Survey laboratory in Salinas, CA. Quality control procedures for this laboratory are available the U.S. Geological Survey.

2.3. Data Reduction

During WY95, total dissolved P (TDP) was assayed for all stream samples along with TP and SRP (30 to 50 assays per stream). Subtraction of TDP from TP yields total particulate P (PP), while subtraction of SRP from TDP yields dissolved organic P (DOP). These four operationally-defined P fractions (TP, PP, DOP, and SRP) are examined for this study only for WY95, due to minimal TDP analyses for the rest of the WY89–96 period (8–12 TDP assays per stream per year). Presentation of the entire WY-89–96 data set examines only TP and SRP.

Although stream water quality records exist from WY81 to the present for certain LTIMP streams, continuous, uninterrupted records for all nine streams did not begin until WY89. The WY89–96 period covers at least 4 yr of drought (WY90, WY91, WY92 and WY94), while the WY81–88 period covered at least 2 yr of drought (WY87, WY88). Both periods encompassed at least 3 relatively high-discharge years (Hatch, 1997). Water Year 95 is considered a high-discharge year.

TABLE II
Mean annual phosphorus parameters for LTIMP streams (WY89–96)

Stream	TP Load (kg)	SRP Load (kg)	TP Conc. ($\mu g\ L^{-1}$)	SRP Conc. ($\mu g\ L^{-1}$)
Blackwood	1927 (1966)	158 (99)	77 (33)	6 (0)
General	324 (262)	63 (41)	24 (6)	4 (0)
Glenbrook	137 (184)	32 (45)	101 (16)	19 (1)
Incline	560 (550)	80 (63)	111 (20)	19 (1)
Loganhouse	9 (11)	1 (1)	33 (4)	4 (0)
Third	1120 (1315)	69 (39)	220 (76)	14 (1)
Trout	1281 (1115)	249 (197)	65 (5)	11 (0)
Upper Truckee	3364 (3010)	451 (372)	61 (5)	7 (1)
Ward	1250 (1261)	149 (116)	63 (40)	7 (1)

All concentration means are discharge-weighted. TP = total P, SRP = soluble reactive P. Standard errors in parentheses.

The representativeness of the WY89–96 data (8 yr) must be interpreted in light of drought conditions common during this period. The use of WY89–96 annual means in this study runs the risk of obscuring water quality differences between high- and low-discharge years within a given stream.

Annual and monthly concentration means were discharge-weighted. Lewis *et al.* (1984) assert that in highly-variable discharge systems in mountainous areas, discharge-weighting gives the best representation of the chemical constituents accumulated in proportion to discharge, more accurately reflecting the conditions of the receiving lake. P loads (mass per unit time) were calculated using the U.S. Geological Survey rating curve method for individual water years, adjusted according to Ferguson (1986). Daily loads were summed for monthly and annual loads.

3. Results

3.1. Annual Phosphorus Loads

Water Year 95 loads were dominated by the PP fraction (19–6824 kg yr^{-1}), which comprised 56–94% of the TP load for LTIMP (Figure 2A). The DOP percentage of TP during WY95 ranged from 3–29%, while SRP load comprised 3–17% of TP load. Mean annual WY89–96 TP loads ranged between 9–3364 kg yr^{-1} (Table II). During the same period, SRP loads (1–451 kg yr^{-1}) were less variable than TP loads, although the relative order of ranking by LTIMP streams was similar. Annual TP and SRP load variation for WY89–96 increased with mean annual load.

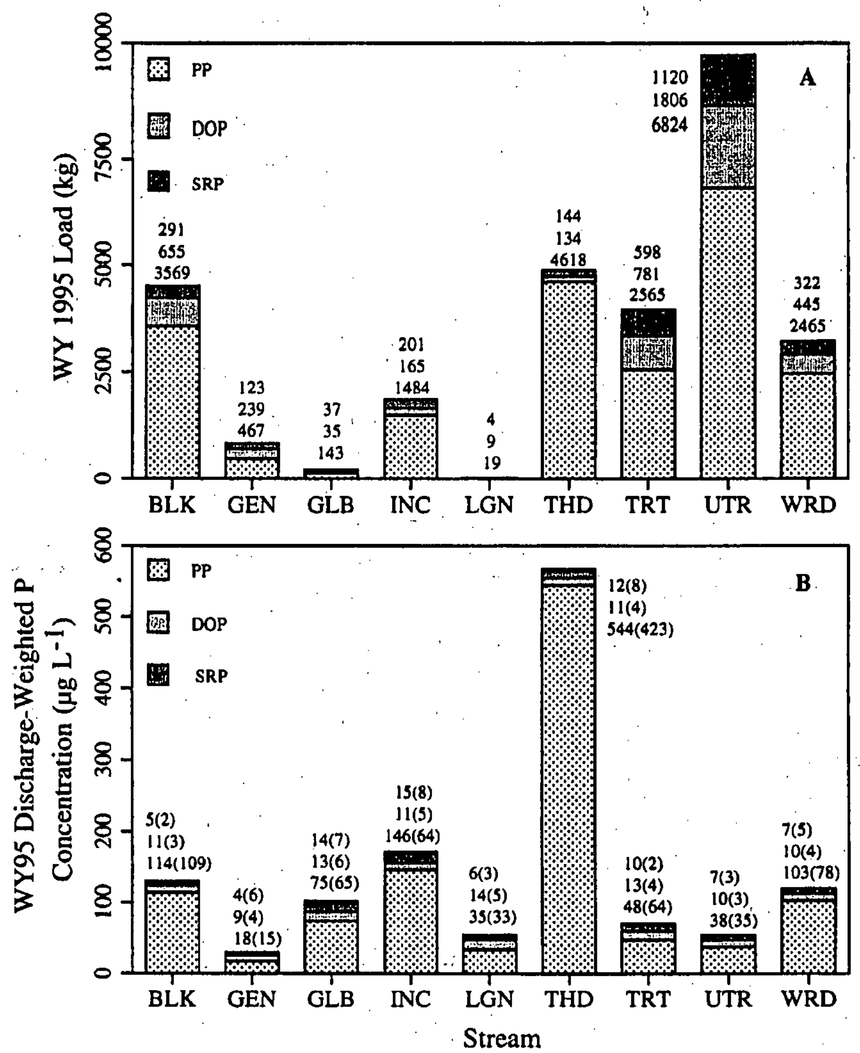

Figure 2. Water Year 1995 annual phosphorus loads and discharge-weighted phosphorus concentration means for Lake Tahoe Interagency Monitoring Program streams. Numbers above bars indicate loads or concentrations (standard errors) for each P fraction (TP = entire bar length). PP = particulate P, DOP = dissolved organic P, SRP = soluble reactive P. See Table I for stream names.

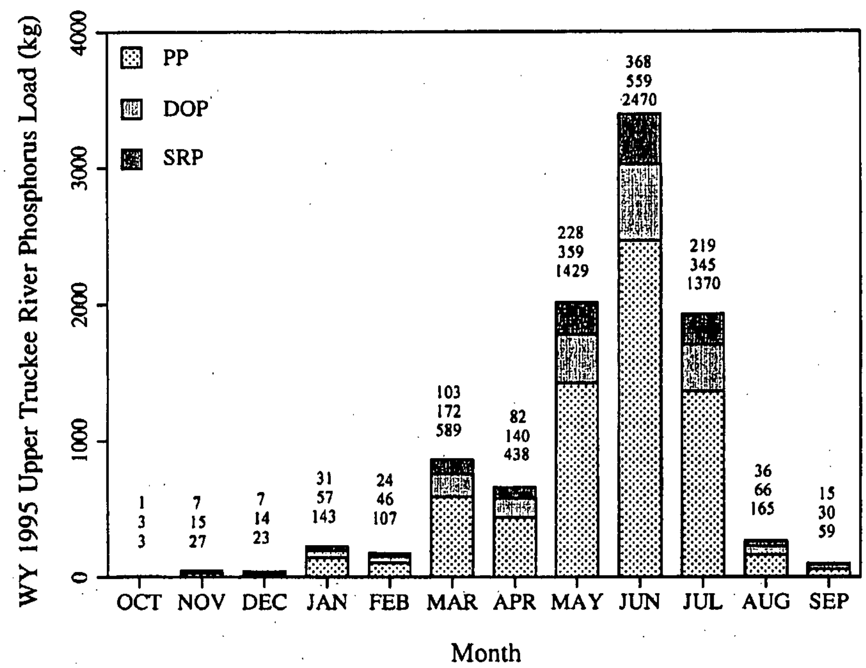

Figure 3. Monthly phosphorus loads for the Upper Truckee River for Water Year 1995. Numbers above bars indicate loads for each P fraction (TP = entire bar length). PP = particulate P, DOP = dissolved organic P, SRP = soluble reactive P. See Table I for stream names.

3.2. Annual Phosphorus Concentrations

Water Year 95 PP (18–544 μg L^{-1} concentrations comprised 58–96% of the TP concentration in WY95 (Figure 2B). Standard deviations for PP in WY95 were similar in magnitude to the annual means (76 to 133% of annual mean). Dissolved organic P (9–14 μg L^{-1}) comprised 2–29% of the mean annual TP, with standard deviations ranging between 27 and 46% of the annual DOP mean. Soluble reactive P (4–15 μg L^{-1}) contributed 2–14% of the TP concentration, with standard deviations between 20 to 150% of the mean annual SRP concentration. Water Year 89–96 TP mean concentrations ranged between 24–220 μg L^{-1} (Table II). Standard errors were generally less than 25% of the annual TP mean, although three streams showed variability between 35–63%. Soluble reactive P concentrations for WY89–96 varied between 4–19 μg L^{-1} with small standard errors ($\leq 1 \mu$g L^{-1}). In general, annual TP and SRP mean concentrations for the WY89–96 period and WY95 were similar.

3.3. Monthly Phosphorus Loads

Hatch (1997) demonstrated that mean monthly WY89–96 TP loads and SRP loads for LTIMP streams peaked at the height of the spring snowmelt, ranging between 4–974 kg month^{-1} and 0.5–124 kg month^{-1}, respectively for May-June. To illustrate, mean monthly WY95 loads for the Upper Truckee River ranged from 3–2470 kg PP month^{-1}, 3–559 kg DOP month^{-1}, and 1–368 kg SRP month^{-1} (Figure 3). During the May-July period, 77% of the PP load, 70% of the DOP load, and 73% of the SRP load occurred, while 92% of the PP load, 87% of the DOP load, and 89% of the SRP load occured during the March-July period.

3.4. Concentration versus Load

For WY95, the top three TP and PP concentration rankings were occupied by Third Creek, Incline Creek, and Blackwood Creek (Table III), which ranked 2nd, 6th, and 3rd, for TP loads. However, the Upper Truckee River ranked 7th for both TP and PP concentrations, but 1st for load rankings. Dissolved organic P concentration ranks were led by Loganhouse, Glenbrook, and Trout Creeks, but their load ranks were 9th, 8th, and 2nd, respectively. Again, the Upper Truckee river ranked 7th for DOP concentration, but 1st for DOP load. Soluble reactive P concentration rankings were led by Incline Creek, Glenbrook Creek, and Third Creek, but these streams ranked 5th, 8th, and 6th for SRP loads, respectively. The overall result these comparisons indicate is that the stream with the highest P concentration does not necessarily have the highest P load, and visa versa.

Examination of P concentration-load ranking differences on a monthly basis (May-June peaks) is best represented by using TP and SRP data from WY89–96 (Table III). The top three TP concentration rankings were occupied by Third Creek, Ward Creek, and Blackwood Creek, which ranked 4th, 3rd, and 2nd for TP loads. The Upper Truckee River, however, was ranked first with respect to TP load, but seventh with respect to TP load, but seventh with respect to TP concentration. The remaining streams ranked lower for both TP concentration and load. Soluble reactive P concentration rankings behaved differently than TP rankings. Although Glenbrook, Incline, and Third Creeks ranked as the top three SRP concentrations for the May/June period, these streams ranked near the bottom with respect to loads (8th, 6th, and 7th respectively). The streams ranking 1, 2, 3 in peak SRP loads (Upper Truckee River, Trout Creek, and Ward Creek) occupied the middle range of SRP concentration ranks at 6th, 4th, and 5th respectively. The lowest ranked streams for SRP concentration (Loganhouse and General Creeks) occupied SRP load rank position of 9th and 5th, respectively. As seen for the WY95 rank comparisons for annual P means, the WY89–96 peak monthly mean comparisons also indicate that LTIMP streams with the highest P concentrations do not necessarily have the highest P loads, and visa versa.

TABLE III
Concentration and load rankings for LTIMP streams

	WY95 Mean Annual Rankings[a]							
Stream	TP Conc. Rank	TP Load Rank	PP Conc. Rank	PP Load Rank	DOP Conc. Rank	DOP Load Rank	SRP Conc. Rank	SRP Load Rank
Blackwood	3	3	3	3	4	3	8	4
General	9	7	9	7	9	5	9	7
Glenbrook	5	8	5	8	2	8	2	8
Incline	2	6	2	6	4	6	1	5
Loganhouse	7	9	8	9	1	9	7	9
Third	1	2	1	2	4	7	3	6
Trout	6	4	6	4	2	2	4	2
Upper Truckee	7	1	7	1	7	1	5	1
Ward	4	5	4	5	7	4	5	3

	Peak Monthly Mean P Values and Ranking for the WY89–96 Period[b]							
Stream	TP Conc.	TP Conc. Rank	TP Load	TP Load Rank	SRP Conc.	SRP Conc. Rank	SRP Load	SRP Load Rank
Blackwood	185	3	713	2	6	6	43	4
General	45	7	114	7	4	9	17	5
Glenbrook	102	5	40	8	16	1	8	8
Incline	147	4	125	6	14	2	16	6
Loganhouse	52	6	4	9	5	8	0.5	9
Third	468	1	329	4	114	3	13	7
Trout	45	7	295	5	9	4	52	2
Upper Truckee	45	7	974	1	6	6	124	1
Ward	260	2	496	3	8	5	46	3

[a] Rankings according to values in Figure 2.
[b] Values represent the annual peak mean monthly values. Concentrations in μg L^{-1}, loads in kg (Hatch, 1997), TP = total P, PP = particulate P, DOP = dissolved organic P, SRP = soluble ractive P.

3.5. Effect of Watershed Characteristics on Water Quality

The task of relating watershed parameters (Table I) and stream water quality parameters was engaged by using an 11-by-21 matrix of mean annual P indices and watershed parameters for each of the nine LTIMP watersheds. Most watershed parameters are fixed geologic or morphologic features. Even the road and development categories can be assumed constant constant because there were no new roads built during the WY89–96 period and development coverage has been strictly reg-

TABLE IV

Inter-watershed linear regression relationships

Dependent variable	Independent variable	Slope	Dependent variable	Independent variable	Slope
Discharge	Basin Area	+	Areal TP Load	none	
	Main Chan. Leng.	+	SRP Load	Basin Area	+
	Chan. Gradient	–		Main Chan. Leng.	+
	Relief Ratio	–		Channel Gradient	–
	Road Length	+		Relief Ratio	–
	Road Coverage	+		Road Length	+
	Non-Road Coverage[a]	+		Road Coverage	+
Areal Discharge	Precipitation	+		Non-Road Coverage*	+
	Basin Aspect	–	Areal SRP load	% Mod. Haz. Land	+
	Relied Ratio	–	TSS Conc.	% Surf. Deposits	+
	% Low Haz. Land	–	TP Conc.	% Surf. Deposits	+
	% Decomp. Granite	–	SRP Conc.	Drainage Density	–
	% Glaciated Granite	+		Road Density	+
TP Load	Basin Area	+			
	Main Chan. Leng.	+			
	Relief Ratio	–			
	Road Length	+			
TP Load	Road Coverage	+			
	Non-Road Coverage[a]	+			

[a] Non-road coverage represents areas covered by buildings and/or areas compacted to the point that surface water can not infiltrate. Watershed parameter values from Table I. Water quality parameters from Hatch (1997). Slope indicates a positive or negative relationship. Significance at the 0.05 level among WY89–96 mean annual water quality and watershed parameters for LTIMP streams.

ulated since 1987. After linear univariate regressions were performed, parameter associations with $p < 0.05$ were considered for additional analysis (Table IV).

Although an important watershed variable influencing discharge, P loads, and P concentrations may not have been measured, it is interesting to note that many watershed parameters did not correlate well with P-related variables in LTIMP streams (Table IV). Our results were surprising since the literature indicates that watershed geology strongly influences water quality (Dillon and Kirchner, 1975; Keller and Strobel, 1982; Grobler and Silberbauer, 1985; Molot *et al.*, 1989). However, a lack of significant associations between catchment and water quality parameters has also been noted by Dillon *et al.* (1991) and Svendsen *et al.* (1995). The LTIMP data inter-watershed discharge was associated positively with basin area and main channel length, but negatively associated with channel gradient and basin relief ratio. Positive associations also existed between discharge and road length, road coverage, and non-road coverage (e.g., buildings, compacted soils). Inter-watershed SRP loads and TP loads were associated with the same parameters as discharge, which is not surprising considering that loads are fundamentally linked to discharge. Inter-watershed areal discharge (liter ha^{-1}) had similar associations as seen for discharge, but was also linked to precipitation. Areal loads (kg ha^{-1}), however, lost many of the associations seen for loads (kg), suggesting that basin area exerts a strong influence on SRP and TP loads in LTIMP streams. Inter-watershed TSS and TP concentrations (and by association PP concentrations, Figure 2) were associated with percent surficial deposits, which are located primarily adjacent to stream channels. Inter-watershed SRP concentrations were correlated with drainage density and road density.

4. Discussion

4.1. Characterization of Tahoe Stream Phosphorus

Phosphorus concentrations and loads in LTIMP streams occur primarily in the particulate form (Figure 2). During the period WY89–96, 63–87% of annual TP concentration occurred as PP for most streams, although Loganhouse Creek (45%) and General Creek (46%) had lower values (Hatch, 1997). Previous stream studies at Tahoe from WY70–73 on Glenbrook Creek, Incline Creek, and Third Creek found TP concentration to consist of 83%, 83%, and 69% PP for these streams, respectively (Glancy, 1977, 1988). The PP fraction comprised 56–94% of annual TP loads during WY95 (Figure 2). Previous studies on Ward Creek in the Tahoe basin showed that 84% of annual TP load was PP (Leonard *et al.*, 1979), which is similar to the 76% value for Ward Creek in WY95. Vaithiyanathan and Correll (1992) found that 77% of P export occurred as PP in forested Maryland watersheds, while Svendsen *et al.* (1995) reported values of 56–77% in a Danish lowland stream. Gaynor (1979) demonstrated that 68% of the annual TP load for southern Ontario streams occurred as PP. Relevant literature data from high-mountain habitats was rare.

Annual mean Tahoe stream SRP concentrations comprised 2–14% of TP during WY95 (Figure 2), and 6–19% of TP during WY89–96 (Table II). Leonard *et al.* (1979) found that the mean annual Ward Creek SRP concentration was 12 $\mu g\ L^{-1}$ over the WY71–74 period (compared to 7 $\mu g\ L^{-1}$ in the present study, Figure 2), however their means were not discharge-weighted. Leonard *et al.* (1979) also found that SRP load comprised 11% of TP load for Ward Creek, which is very close to the 10% value for WY95.

Dissolved organic P concentrations comprised 2–29% of TP during WY95 (Figure 2). Gaynor (1979) found that only 4% of TP was transported as DOP in a highly-agricultural southern Ontario stream. Working in a 6.3 ha flat, deciduous forest watershed in Maryland, Vaithiyanathan and Correll (1992) observed a DOP export of 0.62 g ha^{-1} $week^{-1}$, which translates to 0.2 kg yr^{-1}, much lower than for Tahoe streams. Dissolved organic P concentration was often equal to or greater than SRP (Figure 2), inferring that DOP loads were also greater. Several sources of DOP may be present in Tahoe streams, including periphyton exudates (Perkins, 1976), senescing vegetation, streambank roots and fauna, and abandoned septic leach fields. Meyer (1979) argued that decomposing organics on the stream bottom (e.g. leaf litter) are important sources of DOP, while Kaplan *et al.* (1975) contended that the Ward Creek microbial community is important in the breakdown of stream organic material.

4.2. WATERSHED ATTRIBUTES AFFECTING WATER QUALITY

Lack of significant correlations for many of the variables examined in this study (Table I) may indicate several things. First, correlational analysis for the types of variables chosen may not be appropriate. Water quality variables in the Tahoe basin are highly variable, changing significantly from year to year (Table II). Using mean (or even modal) values may mask the true variability of the hydrologic system, especially when one compares water quality to fixed (non-variable) watershed parameters. Second, it may be the case that despite their seemingly broad range of characteristics (Table I), the LTIMP watersheds are quite similar in their hydrologic behavior. Significant relationships between water quality and catchment parameters are seen in the literature where both the independent and dependent variables have a broad range (i.e., large axes spreads), which are associated with more regional/global data sets (e.g., Jones and Bachmann, 1976; Van Nieuwenhuyse and Jones, 1996). However, it could be the case that on a local scale (e.g., 1000 km^2), important watershed parameters that drive water quality are actually the same. The significant correlations that did exist in the LTIMP data set suggest that discharges and stream P loads are strongly associated with precipitation, basin area, and basin steepness. The values of these variables may appear quite different when compared on the scale of the Lake Tahoe basin (Table I), but may appear quite similar when compared to a data set from a more regional, national, or global scale.

It may be the case, however, that streambank erosion is the primary variable driving sediment and P transport in the LTIMP streams. Stormwater runoff enhanced by human activities not only carries debris and nutrients, but is also causes heightened storm hydrograph pulses (Beaulac and Reckhow, 1982; Ward and Elliot, 1995). Stormwater pulses to streams occur because road and storm drain systems focus water into a relatively small area much more quickly than most natural systems. These pulses create higher water velocity and water quantity conditions than which natural stream systems have evolved (Beaulac and Reckhow, 1982), increasing the potential for erosion higher up on streambanks.

Overland flows have not been observed frequently in the Sierra Nevadas (Skau *et al.*, 1980). Rarity of overland flow in forested catchments has also been demonstrated in New Hampshire (Meyer and Likens, 1979), the eastern United States (Beaulac and Reckhow, 1982), and Japan (Chikita, 1996). Coarse, sandy soils and thick layers of forest duff in the Tahoe basin most likely allow water to easily percolate into the soil. Much precipitation probably reaches Tahoe streams via groundwater (subsurface quickflow), implying that in forested catchments the major sediment/nutrient sources to streams come from channel and/or near-channel sources (Walling, 1983; Dedkov and Moszherin, 1992; Svendsen *et al.*, 1995; Chikita, 1996).

Streambank erosion has been cited as the main source of TSS in Tahoe streams in several studies (Leonard *et al.*, 1979; Hill and Nolan, 1990; USDA Forest Service, 1994). Mountain stream bottom sediments have been shown to come from streambank erosion (Chikita 1996), often as coarse particulates (Fenn and Gomez, 1989) which can be deposited and redeposited several times along the course of a stream (Walling, 1983). Heavy armoring and stairstepping in mountain streambeds dissipates much of the energy caused by steep stream slopes, greatly limiting the amounts of sediment originating from stream bottoms (Skau *et al.*, 1980). Stream PP sources (by association with TP and TSS) are closely tied to streambank and/or streambed erosion (Svendsen *et al.*, 1995). Quantification of sediment movement from this source would tell us how significant streambank erosion's contribution is to the overall transport of stream sediment and P to Lake Tahoe.

4.3. Human Development Impacts on Water Quality

Since there is no pre-development water quality data for the LTIMP watersheds, directly differentiating the natural and the human impact contribution to P delivery is difficult. The General Creek watershed, however, is considered a 'control' with regards to human development because it is located in a state park. If one characterizes P transport in General Creek and applies these relationships to a nearby developed creek, one can predict what P transport would be like if that nearby watershed had similar geomorphic and geological characteristics but never experienced human distrubance. This technique enables a preliminary differentiation between natural and human-influenced P delivery. Hydrologists commonly use the relationship between discharge and morphometry in gauged watersheds to predict discharge in ungauged watersheds (Yaksich *et al.*, 1985). Of the monitored watersheds adjacent to General Creek, Ward Creek is the best candidate for comparison. Although Blackwood Creek is closer to General Creek (Figure 1), extensive stream channel alteration, gravel mining, and cattle grazing have altered Blackwood Creek significantly. The Ward Creek watershed has not been altered to such a great extent, with housing subdivisions and roads being the only major human influence. General and Ward Creeks have approximately the same precipitation amounts, vegetation types, and basin area (Table I).

A simplistic 'model' of TP loading is depicted in Figure 4A in which annual areal TP load is significantly related to annual discharge for General Creek, Al-

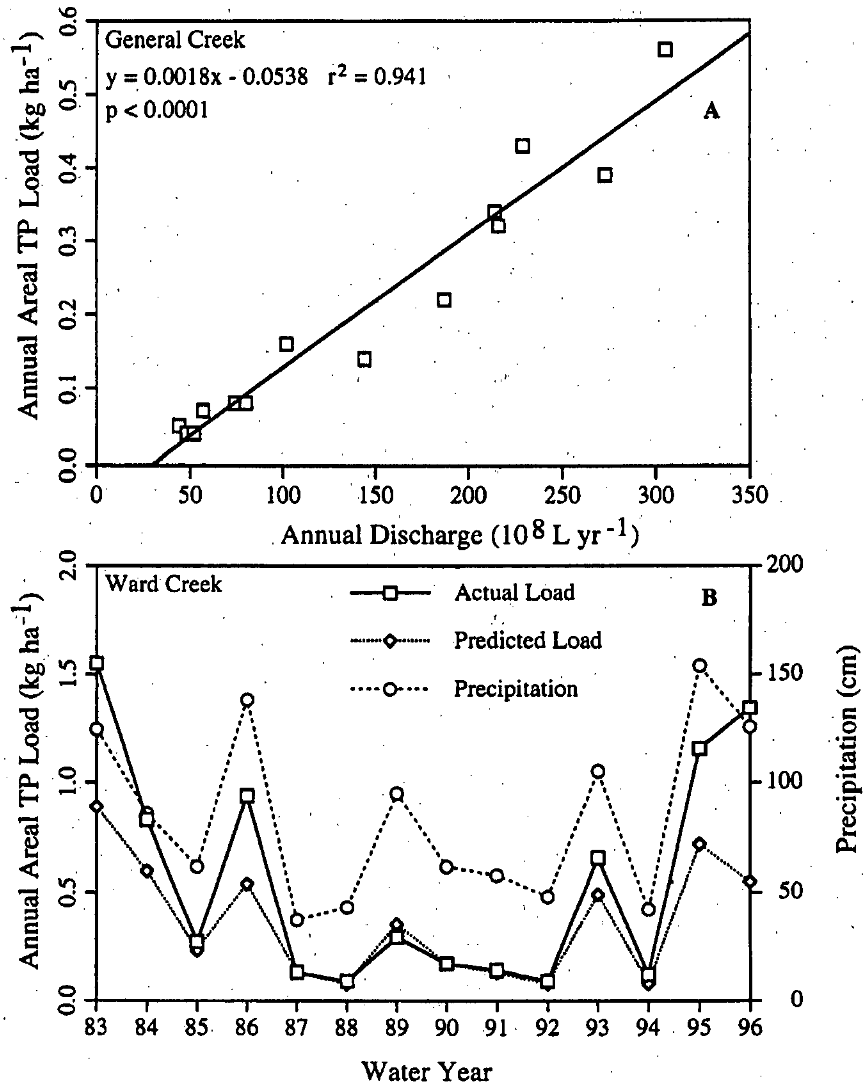

Figure 4. Relationship between discharge and areal TP load for General Creek (Water Years 1983–1996); actual and predicted areal TP load for Ward Creek (see Discussion). Precipitation from Tahoe City, CA station.

though TP load is fundamentally linked to discharge, this 'model' is intended only for predictive purposes.

If it is assumed that current discharge in Ward Creek would be characteristic of undeveloped conditions, the discharge for Ward Creek can be substituted into the equation generated for General Creek in Figure 4A. The results of this extrapolation indicate that Ward Creek areal TP loading would be much lower during high precipitation and discharge years (Figure 4B) if the watershed had no development. Water Years 1983, 1984, 1986, 1993, 1995, and 1996 received above-average precipitation and thus Tahoe streams received above-average discharges. Water Year was unusual in that almost all precipitation occurred during a single March 1989 snowstorm; drought conditions were essentially still in effect for the year. Ward Creek's actual measured load exceeded the predicted load during above-average precipitation years, suggesting that Ward Creek responds to the effects of human development primarily during high-discharge years. The model estimated that human development increased areal TP loading over background levels by 73% in WY83, 39% in WY84, 74% in WY86, 33% in WY93, 58% in WY95, and 144% in WY96.

5. Conclusions

The results of this study indicate that stream P loads to Lake Tahoe come primarily from streams with the greatest discharge during the spring snowmelt. Particulate P is the predominant P form transported throughout the year, and is associated with total suspended sediments. Results also suggest that the impact of human development on stream P loads will be most evident during high discharge years. Hence the identification of stream sediment and P sources and their contributions to stream loads is of great interest in both a scientific and management context. Because stream P loads are highly variable, maintaining the stream monitoring network is necessary to statistically distinguish changes in water quality resulting from landscape best management practices from those due to inter-annual climatic influences.

Streambank erosion has been identified as a potentially significant source of sediment in the present study and in past investigations on Tahoe streams. Determining the overall contribution of streambanks to stream suspended sediments is necessary to indicate whether restoration of these areas will result in significant reductions of stream sediment and P transport to Lake Tahoe. A thorough quantification of stream sediment contributions from roads and impervious surfaces is also needed. Is the impact of these sources on stream sediment due more to sediment transported *from* these sources, or due more to their enhancement of streambank erosion due to quicker stream hydrograph pulses, higher stream velocities, and higher stream stages? The answer can help direct watershed restoration efforts in the Tahoe basin and in other developed subalpine watersheds.

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