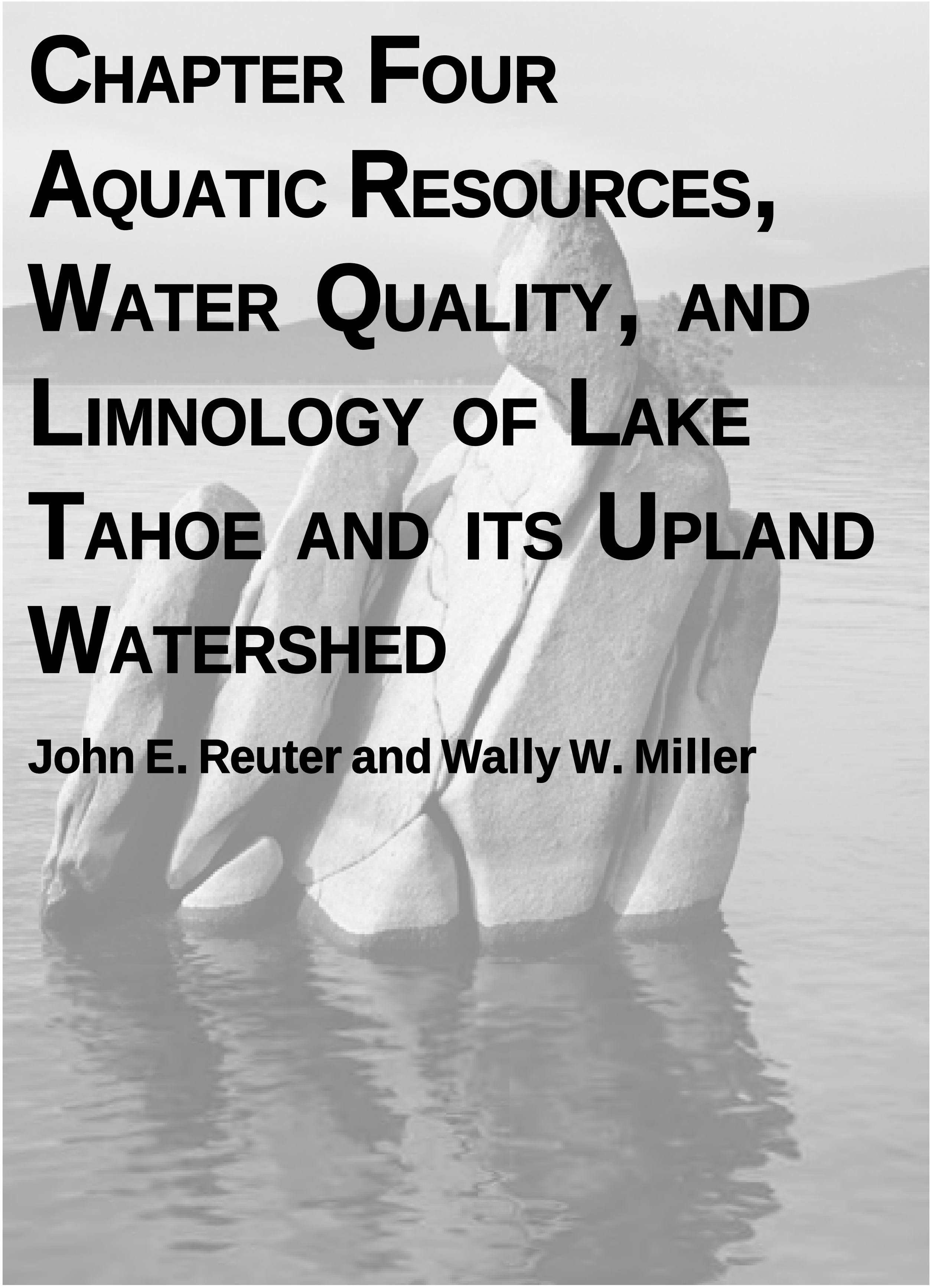


Chapter Four Aquatic Resources, Water Quality, and Limnology of Lake Tahoe and its Upland Watershed

John E. Reuter and Wally W. Miller

CHAPTER FOUR

AQUATIC RESOURCES, WATER QUALITY, AND LIMNOLOGY OF LAKE TAHOE AND ITS UPLAND WATERSHED

John E. Reuter and Wally W. Miller

Water quality in Lake Tahoe has been evaluated continuously since the early 1960s, and algal growth has been increasing at a rate greater than five percent per year. Correspondingly, there has been a decline of clarity at an alarming rate of nearly one foot per year. This long-term trend is statistically significant and now can be perceived by even the casual observer. If the loss of clarity continues, it is predicted that the lake will have lost approximately 20 meters of transparency by 2030. The resulting Secchi depth of 12 meters will no doubt be accompanied by a change of lake color and a permanent change in trophic status.

Today, significant portions of the once pristine basin are urbanized. Studies from 1962 to 1999 have shown that many factors, such as land disturbance, habitat destruction, air pollution, soil erosion, and roads, have all interacted to degrade the basin's air quality, terrestrial landscape, and streams, as well as the lake itself. However, some of the same features that maintained the exceptional historical water quality in Lake Tahoe now threaten its future. Once nutrients enter the lake they remain in the water and can be recycled for decades. As a consequence, these pollutants accumulate over time and contribute to Lake Tahoe's progressive decline. The ability of the lake to dilute nutrient and sediment loading to levels where there is no significant affect on lake water quality has been lost.

The Tahoe basin is a complex ecosystem with 63 individual watersheds and numerous intervening areas. Much urbanization is in the intervening areas that drain directly to the lake. It is unrealistic to expect that completing any single mitigation project will have a significant effect on lake water quality. It is clear that future research and monitoring must address such issues as the effectiveness of best management practices (BMP), the potential reduction of nutrient and sediment loading, with its subsequent impact on the nutrient budget and lake response, project design, project monitoring, and priority ranking. This approach is critical to the future of restoration efforts in the basin. Management needs a comprehensive watershed approach. Agencies require technical products to more specifically identify sources of nutrients and sediment, to assess the effectiveness of restoration BMPs, and to help guide erosion control prioritization as project implementation begins to ramp up in magnitude.

While sediments and nutrients are the major problems that must be addressed to meet desired conditions for lake clarity and algal growth, other pollutants also affect aquatic ecosystem processes. These include MTBE and other boat fuel chemicals, toxic organic chemicals, such as pesticides and PCBs, and materials leaking into the ground water from underground storage tanks. The scope of this portion of the watershed assessment focuses primarily on the issue of lake clarity; however, this focus does not imply that these additional water quality issues are not of concern.

The Role of Science-based Decision-making in Adaptive Watershed Management

For effective lake management, understanding is needed of the following:

- What are the specific sources of sediment and nutrients to the lake and what are their respective contributions?
- How much of a reduction in loading is necessary to achieve the desired thresholds or total daily maximum loads (TMDL) for Lake Tahoe (i.e., lake response)?
- How will this reduction be achieved?

The watershed approach taken at Lake Tahoe for many decades recognizes that lake water quality is linked to upland watershed processes and air quality. Natural watershed processes have been affected by the disruption of natural ecosystem processes that treat runoff naturally (e.g., wetlands, ground water infiltration, and vegetation) and a changed landscape that alters hydrology and promotes the accelerated loading of nutrients and sediment (e.g., impervious cover, road network, habitat disruption, and land disturbance). Successfully implementing land, air, and water quality restoration projects is considered the only realistic avenue to arrest further decline in lake clarity. Scientific efforts must be focused on restoration objectives and must be coordinated to obtain information needed for adaptive management.

Hundreds of scientific papers and reports have been written on many aspects of Lake Tahoe, its watershed, and its water quality since studies first began more than 40 years ago. This chapter of the watershed assessment uses a significant portion of this information to answer a series of questions associated with the following three critical issues:

- Issue 1—The need to understand and quantify, where possible, the links between urban and natural features of the watershed landscape and the loading of nutrients and sediments to Lake Tahoe.
- Issue 2—The need to determine the extent to which discharge of sediment and nutrients from basin watersheds can be effectively reduced by management or restoration activities.
- Issue 3—The need to understand how Lake Tahoe will respond to watershed restoration projects.

The goals of this chapter can be summarized by the products it provides, which include:

- A comprehensive review of past studies with the focus of assessing both upland and lake water quality (a review of this magnitude is lacking for the Tahoe basin);
- A focal point that consolidates current and future knowledge;
- A roadmap for future proposed research and monitoring;
- New scientific information on a number of critical issues, including the decline of dissolved oxygen in portions of Lake Tahoe and the effects of fire (prescribed or natural) on nutrient cycling; and
- A review of important hydrologic and ecological processes in the Tahoe basin that require consideration during formulation and implementation of restoration projects and strategy.

The assessment was successful even prior to the publication of this final report in that it has served to galvanize scientific thought in the basin and to reinforce the importance of applying adaptive management at the watershed level.

In the remainder of this summary, the salient findings reported in this portion of the assessment are presented. In particular, focus is placed on those findings with direct and immediate application to restoration and adaptive management. This chapter does not provide a prescriptive formula for restoration; rather it provides key information for science-based decision making. Equally as important, it emphasizes those areas where the existing knowledge is insufficient.

Environmental Setting

Lake Tahoe lies at the crest of the Sierra Nevada at an elevation of 1,898 m within both California and Nevada. The drainage area is 812 square kilometers (km^2), with a lake surface of 501 km^2, producing a ratio of only 1.6. The lake is in a montane-subalpine watershed dominated by coniferous vegetation and nutrient-poor soils. Sixty-three streams flow into the lake. At 505 m, Lake

Tahoe is the world's tenth deepest lake, with a mean depth of 313 m. Its volume is 156 km^3 with a residence time of about 700 years, and the lake is ice-free year-round. The depth of vertical mixing varies from 100 m to >450 m, depending on winter storm intensity. The extent of mixing is directly related to interannual differences in algal growth because of the introduction of nutrient-rich water from the deeper portions of the lake (Goldman and Jassby 1990). The amount of algal primary productivity during the extended summer season is fueled by nutrients that mix up from the bottom waters, enter the lake via surface and subsurface runoff, are loaded by atmospheric deposition to the lake surface, or are recycled by bacteria and other aquatic micro-biota. Lake Tahoe was once classified as ultra-oligotrophic (Goldman 1974); i.e., low nutrient content, low plant productivity, and high transparency. However, because of the ongoing decline in clarity and rise in algal growth rate, its trophic status (level of fertility) has been moving toward a meso-oligotrophic status.

Changing Water Quality

Many of the world's lakes have been subject to cultural eutrophication. The anthropogenic enrichment of waters usually results from nutrients reaching a stream or lake from septic tanks and sewage treatment plants, agricultural and urban runoff, or the disturbance of land during lumbering or urban development. These additional sources typically occur at rates that greatly exceed natural inputs. When nutrient content is too high the resulting dense growth of algae causes a change in the lake's color, reduce light penetration, and lower dissolved oxygen to a point where aquatic organisms can no longer survive. Because of Lake Tahoe's naturally low fertility it historically has been a pristine waterbody. However, extensive research and monitoring has provided clear evidence of the onset of cultural eutrophication in oligotrophic Lake Tahoe (Goldman 1988). Continuous long-term evaluation of lake chemistry and biology since the early 1960s has shown that algal production is increasing at a rate greater than five percent per year, with a corresponding decline of clarity at the alarming rate of approximately 0.3 meters, or 1.2 feet, per year. Not only is the long-term trend of declining clarity statistically significant ($p<0.001$), it is now visually obvious. Secchi depths typically range from >15 to <25 m, depending on season and year.

Lake water clarity is measured using a number of techniques. Most commonly, clarity is expressed as a Secchi depth: the depth at which an eight-inch white disk is no longer visible from the surface as it is lowered into a waterbody. Regular measurements at the UC Davis/Tahoe Research Group Index Station began in 1967 and have been made on average every 12.2 days since then (Jassby et al. 1999). In earlier synoptic studies of lake primary productivity, Goldman found the Index Station to represent whole lake conditions (Goldman 1974). Scientific data shows that Secchi depth is directly related to the amount of suspended matter in the water (Jassby et al. 1999). This suspended matter is composed of both biotic materials and suspended inorganic silt or sediment

Extensive research on the spatial distribution of free-floating algae indicates a marked correspondence between the highest algal growth rates and the most extensive shoreline development. Lakewide studies have shown that the central portion of the lake historically has been characterized by relatively fewer algae, with areas near south and north shore developments exhibiting enhanced production. Similar studies of the attached algae also demonstrate this pattern. The dramatic differences in algal growth on rocks at various shoreline locations are linked to nearby development and are immediately visible to the largely shore-bound populace.

Ironically, some of the same features that maintained the exceptional historical water quality in Lake Tahoe now threaten its health under current conditions of increased nutrient and sediment loading. Tahoe's large depth and volume once acted to dilute pollutants to a level of no significant affect; this is no longer the case. Once nutrients enter the lake they accumulate in the water and are available for use over and over for decades. This phenomenon has crucial implications when the results of watershed mitigation and restoration projects are evaluated.

Research also has shown a fundamental shift of algal growth by nitrogen additions from frequent stimulation to almost exclusive phosphorus stimulation (Goldman et al. 1993). This response of

Lake Tahoe algae to nutrient enrichment has been measured since the 1960s, with the observed shift occurring in the early 1980s. Since phosphorus is typically transported along with sediment, these findings underscore the importance of sediment control and erosion mitigation. Atmospheric deposition of nitrogen from both in-basin and out-of-basin sources is now considered a significant factor contributing to the observed shift in nutrient stimulation (Jassby et al. 1994). Because much of the phosphorus input to the lake is still derived from the watershed, erosion control, acquisition of sensitive lands, and other watershed restoration practices remain an appropriate course of action. The focus of much of the current research is erosion and the transport of sediment and phosphorus to Lake Tahoe.

Another important finding is that Tahoe stream water can stimulate the growth of algae (Goldman and Armstrong 1969; Hatch 1997). Stream water quality data, collected as part of the Lake Tahoe Interagency Monitoring Program (LTIMP) from the Upper Truckee River (the major tributary to the lake, contributing approximately 25 percent of the annual flow) has monitored the magnitude of suspended sediment flowing into Lake Tahoe from this tributary. While the annual load of material varies from year-to-year depending on precipitation and land use, as much as 22,000,000 pounds of sediment can enter the lake in a single year from this river alone (Hatch 1997). Indeed, taking nine intensively studied streams in the basin, the annual amount of phosphorus entering Lake Tahoe from watershed runoff was determined to depend directly on sediment concentration (r^2=0.89, $p<0.001$). Given that annual and instantaneous total phosphorus concentrations in the Upper Truckee River at South Lake Tahoe exceed California state water quality standards, controlling erosion and sediment transport and treating surface runoff are crucial aspects of watershed management at Lake Tahoe.

Deep sediments at the bottom of lakes serve as a reservoir of history within the watershed. A recently completed investigation has shown that the rate of sedimentation has varied over the last hundred years (Heyvaert 1998). In particular, rates increased significantly during the Comstock Silver Mining Era (1850 to 1890), when clear-cut-type logging occurred extensively in the Tahoe basin, and again from 1950 to the present. This latter occurrence is believed to be due to increased population growth, road construction, and general urbanization within the basin. The intervening period, (1900 to 1940), showed a reduction in sedimentation and provides hope that the system may respond to proper management.

Fate of Lake Tahoe's Famous Clarity

If the rate of decline in clarity continues, it is predicted that over the next 30 years Lake Tahoe will have lost over half its extraordinary transparency. In total, the lake will have lost approximately 20 meters of transparency by 2030. The resulting Secchi depth of 12 meters will no doubt be accompanied by a change of water color. A change of this magnitude already has been seen from studies in the polluted regions of Lake Baikal, Russia (Goldman et al. 1996).

Link Between Science and Policy for the Benefit of Lake and Watershed Management

One of the critical cornerstones of watershed management is a comprehensive understanding of hydrologic, atmospheric, and ecological processes and their interactions, real-time assessment of environmental conditions (e.g., air quality, water quality, and forest health), response to anthropogenic and natural disturbance, and the ability to predict environmental improvement based on various management strategies. Indeed, serious concerns regarding ecological condition and long-term environmental protection underscore the need to provide the highest quality science to aid in problem resolution (Goldman 1998). Ecosystem health, sustainable environment, and watershed management are interrelated and support growing view that the fabric of the natural landscape is a complex weave of interacting influences, including physical, chemical, and biological factors. Time after time, valid scientific data, with unbiased interpretation, has provided decision-makers in the Tahoe basin with valuable information and insight. Without a sound scientific foundation, critical discussions are too easily misdirected toward narrowly focused interests.

As evidenced by its special status as Outstanding National Resource Water under the Clean Water Act, Lake Tahoe is unique and must be protected. The agency approach for decades at Tahoe has focused on watershed management to protect water quality; this is clearly stated in the Lake Tahoe Basin 208 Plan and is central to the mission of nearly all basin resource agencies. Indeed, the creation of the Tahoe Regional Planning Agency (TRPA), the USDA Forest Service Lake Tahoe Basin Management Unit (LTBMU), and the California Tahoe Conservancy (CTC) speak to the importance of watershed management. A wide array of public and private institutions now forms an extensive foundation for linking policy to scientific research and monitoring.

A critical component for long-term planning at Lake Tahoe is a water quality model, based on the lake's assimilative capacity to receive and process sediment and nutrients (Reuter et al. 1998a, c). By knowing the level of nutrient loading required to achieve the thresholds, responsible agencies will be able to plan in a more quantitative and progressive manner. Based on previous and ongoing research and monitoring, these types of predictive models are being developed.

Watershed Assessment Focus

The watershed approach that has been taken at Lake Tahoe for many decades recognizes that lake water quality is inexorably linked to upland watershed processes, including nutrient cycling, stream flow, surface runoff, ground water, and direct precipitation (Leonard et al. 1979; Glancy 1988; Sullivan et al. 1996). This largely occurs through the hydrologic and biologic cycles that mediate the discharge of nutrients and sediments to the lake. Those normal cycles have been affected by the disruption of natural ecosystem processes that naturally treat runoff (e.g., wetlands, ground water infiltration, and vegetation) and a changed landscape that alters hydrology and promotes the accelerated loading of nutrients and sediment (e.g., impervious cover, road network, habitat disruption, and land disturbance).

This watershed assessment is intended to serve a number of purposes. First, it allowed scientists to conduct a comprehensive review of past studies with the focus of assessing both upland and lake water quality. Evidence for long-term trends is presented along with information on important ecological and hydrological processes. A review of this magnitude is largely lacking for the Tahoe basin. Second, it provides all agency and university scientists, policy-makers, interested organizations, and the concerned public with a single document that serves to consolidate current knowledge. This assessment is intended to serve as a major and substantive reference resource. Third, the format of the assessment, based on issues and questions, provides a roadmap for future proposed research and monitoring. By its very nature, scientific research depends heavily on the results and lessons from previous investigations. Fourth, the contributors to this section of the document also have conducted a number of new analyses; for example, the decline of dissolved oxygen in portions of Lake Tahoe now has been identified and its ramifications have been considered, and the effects of fire (prescribed or natural) on nutrient cycling have been further quantified. The assessment also has provided the opportunity to develop a nutrient budget for Lake Tahoe, documenting both sources to and losses from the lake. Finally, the assessment process has allowed aquatic scientists to begin the important discussion of aquatic environmental indicators, monitoring, and research in a much more integrated fashion.

While focusing on these three key issues, this assessment did not attempt to review all existing information on pollutants that are not either sediments or nutrients. Prominent examples include PCBs found in lake trout flesh (Datta et al. 1998), MTBE (Allen et al. 1998; Boughton and Lico 1988) and other manufactured organic compounds (Lico and Pennington 1999).

The upland watershed and lake sections of this chapter, issues one and three are intended to assess the current state of knowledge regarding these topics (issues 1 and 3 above). These subjects, the focus of most research and monitoring at Lake Tahoe, constitutes the major portion of this chapter's content. However, on the basis of collective experience and from extensive conversations with numerous environmental scientists at Lake Tahoe, it is clear that future research and monitoring must address such issues as effectiveness of BMPs used for restoration and water quality treatment, potential reduction of nutrient and sediment loading and its subsequent impact on the nutrient budget, and such factors as lake response, project design, project monitoring, and priority ranking. This approach is critical to the future of restoration efforts in the basin and is discussed as part of Issue 2.

Issue 1: Upland Water Quality In The Tahoe Basin, With Emphasis On Sediment And Nutrient Discharge

With contributions from John Warwick, Lorin K. Hatch, Charles R. Goldman, Scott H. Hackley, Shari Silverberg, Kyle Comanor, Sherman Swanson, Andrew Stubblefield, and Ted J. Swift

What are the current sources and sinks of nutrients to Lake Tahoe? How do these compare to previous periods of disturbance and restoration since the mid-1850s?

Much of the strategy for lake/watershed management has come about in response to long-term decline in clarity and increase in algal growth rate since the 1960s (Goldman 1988; Jassby et al. 1999). For decades, planning, regulatory, and implementation actions have focused on controlling nutrient and sediment inputs to the lake. Examples include, but are not limited to, the acquisition of environmentally sensitive lands, building restrictions, BMP retrofitting, erosion control, BMPs for treatment of surface runoff, permits, and education.

It is now more important than ever that a nutrient budget that quantifies the critical sources and sinks of nutrients and sediment in Lake Tahoe be completed. In simplistic terms, nutrient input (I_{nut}) is equal to nutrient output (O_{nut}) plus nutrient storage in the lake (S_{nut}). To reduce accumulation in the lake, which is a fundamental goal of management, inputs must be diminished or outputs (sinks) must be enhanced. For large lakes such as Tahoe, management strategies for significantly increasing outputs are not feasible. The water clarity model described in this assessment is intended to help predict the consequences of nutrient/sediment control on lake transparency; however, a nutrient budget is needed to identify the most important sources of loading.

Nutrient Budget Components

Reuter et al. (1998a) provided a preliminary nutrient input budget for Lake Tahoe in which five major sources of nutrients to Lake Tahoe were identified: (1) direct wet and dry atmospheric deposition, (2) stream discharge, (3) overland runoff directly to lake, (4) ground water, and (5) shoreline erosion. The major losses include material settling from the water column to the bottom and discharge to the Truckee River outflow. This section provides preliminary estimates for phosphorus and nitrogen loading; however, in order to begin prioritizing and evaluating the potential contribution of planned restoration projects, a much more in-depth analysis of the specific sources of N and P must be performed.

Nutrient Input

Atmospheric Deposition—Jassby et al. (1994) published a paper estimating the contribution of atmospheric deposition of nitrogen and phosphorus to the annual nutrient loading of Lake Tahoe. This study analyzed atmospheric deposition both as rainfall and dry fallout and then compared this to loading from stream inflow. Six sites were equipped to collect dry fallout and precipitation, and data used in this analysis included the period from 1989 to 1992. Although alluded to in a 1985 report to TRPA (Radian Corporation 1985) and again in 1988 (Papadopulos & Associates, Inc. 1988) the Jassby study represented the first published research to conclude that atmospheric deposition provides most of the dissolved inorganic nitrogen and total nitrogen to the annual nutrient load of Lake Tahoe. It was further concluded that atmospheric deposition also contributes significant amounts of soluble reactive-P and total-P (TP) loading but to a less extent. Comparisons of atmospheric loading at the Ward Creek Lake Level location showed that (1) deposition of nitrate and ammonium were similar, (2) wet deposition of nitrate and ammonium in the forms of snow and rain had approximately twice the loading rate than deposition from dry fallout, (3) conversely, the loading of dry soluble reactive-P was 2.4 times that for wet, (4) the ratio of total-N to dissolved inorganic-N (i.e., nitrate plus ammonium) was 2:1, with dry fallout comprising 64 percent of total-N deposition, and (5) the ratio of total-P to soluble reactive-P was also just over 2:1, with dry fallout comprising 70 percent of total TP deposition.

Annual wet deposition rates for nitrate and ammonium were compared at seven sites in California and one Nevada site close to Lake Tahoe, where the measurements are taken by the National Atmospheric Deposition Program (NADP). The data for Lake Tahoe was judged to be consistent with the two other Sierra Nevada stations located at Yosemite and Sequoia national parks. Note that this database was not sufficient and was it not intended to separate in-basin versus out-of-basin sources. However, Jassby et al. (1994) did hypothesize that nitrogen could have both in- and out-of-basin sources, while soluble-P most likely would have had an in-basin terrestrial source. At this time, P present in wet and dry fallout is hypothesized to result from wood smoke (fires in the forest and wood stove use) and from road dust and aeolian (wind) transport from disturbed land. These conclusions and hypotheses have lead to a more comprehensive exploration of atmospheric nutrient sources, both as part of this assessment and activities of the newly formed Air Quality Modeling Group for Lake Tahoe.

Using these data in concert with other portions of the historic monitoring database and the TRPA isohyetal map for Lake Tahoe (which shows the spatial distribution of precipitation over the entire lake and watershed), loading values for N and P that fall directly on the lake surface were estimated for this assessment. Nutrients deposited on the watershed that are subsequently transported to the lake are included in the calculations of stream discharge, direct runoff, and ground water loading. The database used for calculations in this section includes Ward Valley Lake Level Station, 100 m from lakeshore at an elevation of approximately 1,895 m (1983 to 1992); Ward Valley Bench, 6.8 km west of lakeshore at an elevation of 2,200 m (1983 to 1992); anchored buoys at four lake stations, three forming an east-west transect from Ward Valley to mid-lake and the remaining one offshore of South Lake Tahoe (1986 to 1992); and stations in Glenbrook, Nevada, and Incline Village, Nevada, which were operational only in Water Year 1982.

For bulk deposition (wet plus dry), the estimated rates for both nitrate and ammonium ranged from 250 to 450 $\mu g/m^2/day$, depending on location. Typically, the open water portions of the lake were characterized by concentrations at the lower end of this range. Estimates of bulk soluble reactive-P deposition ranged from approximately 15 $\mu g/m^2/day$ along the south shore to 55 $\mu g/m^2/day$ near Glenbrook. For TN minus nitrate+ammonium, bulk deposition ranged from 580 to 1,025 $\mu g/m^2/day$; TP minus SRP ranged from 20 to 65 $\mu g/m^2/day$, again depending on location.

Based on the distribution of deposition measurements and the pattern of precipitation denoted by isohyetal contours, the lake was divided into eight regions. Within each region, the deposition rate was multiplied by the area to determine bulk deposition. The data below represent conditions during the period from 1989 to 1993 and can be entered into the lake's overall nutrient budget:

	Atmospheric Deposition (metric tons per year)	
	Nitrogen	Phosphorus
Soluble	107	5.6
Particulate	128	6.8
TOTAL	234	12.4

For the entire lake surface area, the contribution of P was an estimated 12.4 MT, where 1 MT = 1,000 kg or 2,205 pounds. Direct N-loading to the lake surface was estimated at 234 MT. This accounts for 27 percent and 56 percent of the annual TP and TN budgets, respectively.

Variability in these estimates is driven by a number of factors, including adequacy of sampling site coverage, year-to-year variability, and coverage of events throughout a single year. Measurements of the nutrient content of atmospheric deposition in the Tahoe basin have been very limited. At this time, only the Tahoe Research Group's (TRG) two sites in

Ward Valley and their mid-lake location are of sufficient duration to estimate interannual variability. The other data used in this analysis represent what is currently available. Despite its potential importance to the lake's nutrient budget, sufficient attention has not been given to establishing additional long-term collection sites elsewhere around the lake. It is difficult to quantify the variability resulting from a limited sampling network; however, based on the available data for the Ward Lake level, Incline Village, Glenbrook, and the four lake stations cited previously, the coefficient of variation (mean÷standard deviation) for bulk nitrate deposition (μmol N/m^2/d) is 22 percent. Similarly, the coefficient of variation for bulk ammonium and soluble reactive-P deposition are 24 percent and 36 percent, respectively.

Year-to-year variability also can be analyzed by examining the wet deposition rates for nitrate, ammonium, and soluble reactive-P at the Ward Lake level station from 1983 to 1992 (Jassby et al. 1994). The coefficients of variation for these parameters were 31 percent, 37 percent, and 43 percent, respectively. For each of these parameters, wet deposition from 1989 to 1993 was within 10 to 20 percent of the values found during the longer 1983 to 1992 period.

Stream Loading—The sixty-three streams that drain into Lake Tahoe are characterized by different levels of urban development and disturbance. The LTIMP has been sampling up to 32 sites in 14 streams since 1980. LTIMP is a cooperative program including both state and federal partners, and is operationally managed by the US Geological Survey, The UC Davis/Tahoe Research Group, and TRPA. The following streams are currently monitored and have been monitored since 1988: Trout Creek, Upper Truckee River, General Creek, Blackwood Creek, Ward Creek, Third Creek, Incline Creek, Glenbrook Creek, Logan House Creek, and Edgewood Creek. Note that because of variation in watershed characteristics around the basin and significant "rain shadow" effects from west to east across the lake, no single location represents all watersheds. Flow from these monitored streams totals 50 to 55 percent of the total discharge from all tributaries. Each stream is monitored on 40 to 60 dates each year. N and P loading calculations were performed using the LTIMP flow and nutrient concentration database.

Data from the early 1980s to the early 1990s were used to calculate the stream loads for N and P, as part of two separate studies (Marjanovic 1989; Jassby et al. 1994). The results for annual N-loading were 81.1 MT and 55.2 MT for the beginning and end of this period, respectively. Comparable loading values for total-P were 12.5 MT, and 11.2 MT. Differences between these periods reflect the variation in precipitation and runoff.

The US Geological Survey (USGS), in a cooperative study with TRPA, also provided a very preliminary estimate of nutrient loading to Lake Tahoe from 1990 to 1993 (Thodal 1997). In this latter study, annual nutrient loads associated with streamflow were estimated by multiplying the mean annual volume of surface-water runoff by the mean annual nutrient concentration. Using this simple approach, loading from runoff was reported as 70 MT for total-N and 20 MT for total-P (Thodal 1997). A very early estimate of streamflow nutrient loading by Dugan and McGauhey (1974) estimated 120 MT of total-N and 9.2 MT for total-P. These data are similar to the other estimates, despite being much older and perhaps having been acquired using different methodologies for nutrient analysis. Taking the mean of these values, which represents different periods and consequently different precipitation conditions, loading estimates of 81.6±27.7 (mean±standard deviation) MT and 13.3±4.7 MT were obtained for total-N and total-P, respectively. These accounted for 20 percent and 29 percent of the N and P budgets.

As part of the joint USGS and TRG analysis of the LTIMP stream flow and loading database, scheduled for completion in 2001, these loading rates will be updated and examined for temporal trends, station-to-station variability, relationship to land use, contribution by various chemical forms of N and P, loading of total suspended sediments, and other features of the long-term data set. Part of that effort will be to calculate loading rates for soluble reactive-P (SRP). As a preliminary estimate for this report, SRP accounted for 18 percent of total-P for the ten primary LTIMP streams sampled between 1989 and 1993. This is exactly the mean SRP:TP ratio found for the Upper

Truckee River (South Lake Tahoe site) from 1981 to 1997.

Direct Runoff—The Tahoe basin has 52 intervening zones that drain directly into the lake without first entering streams. These intervening zones generally are found between individual watersheds and, as such, are distributed around the entire lake. These zones range from 0.1 km^2 to 10.5 km^2. The range for covered or otherwise disturbed land within these intervening zone ranges from 0 to 63 percent. The overall ratio of disturbed land to total area is 27 percent, with runoff from the intervening zones accounting for 10 percent of the entire drainage.

Calculations of loading from direct runoff requires quantifying flow and concentration (flow from each of the intervening areas was calculated by Marjanovic [1989]). Data on N and P concentrations in direct runoff are less available than concentrations from other sources because this type of study has not received priority funding in the basin. However, based on a study of urban runoff at south shore in 1983 to 1984 by the Lahontan Regional Water Quality Control Board (RWQCB) (1984), four runoff studies conducted by the TRG between 1993 and 1998 (Ski Run, Pioneer Trail, Upper Truckee Road, and a current study in the 4.3 km^2 intervening area between Ward Creek and the Truckee River outflow), concentration data can be estimated. Clearly, a significant amount of new monitoring that focuses on urban runoff, which is not monitored at the LTIMP stream sites, is still needed.

For the purpose of calculation, an area was considered urban if 25 percent or more of its areas was classified as covered or disturbed. Concentrations representative of urban and nonurban conditions were taken from the field studies cited above and were used in the quantification of loads. Values represent mean±standard deviation and are expressed as mg/L.

	Urban	Nonurban
TSS	238±234	45±28
Total Kjeldahl Nitrogen (TKN)	1.01±0.62	0.33±0.11
Nitrate	0.03±0.02	0.03±0.03
TP	0.43±0.13	0.07±0.03
SRP	0.14±0.05	0.02±<0.01

These concentrations are based on a rather limited database. As discussed elsewhere in this assessment, a comprehensive and well-designed monitoring program for urban and direct runoff must be initiated.

N-loading was calculated at 41.8 MT, or 10 percent of the total-N budget, while P-loading was 15.5 MT, or 34 percent of the total-P budget. Runoff values calculated by Marjanovic (1989) for each intervening zone were used in concert with the measured concentration values. The percent contribution of SRP to TP for direct runoff was estimated at 32 percent, based on the concentration levels. The observation regarding the high contribution of P-loading from direct runoff is particularly important because a significant portion of the urbanization at Tahoe is found in the intervening zones.

Ground Water—Later in this section, a summary of the knowledge of ground water processes in the Tahoe basin is presented; however, quantitative estimates documenting the contribution of ground water discharge to the lake's nutrient budget is limited. The most comprehensive basin-wide effort to date comes from Thodal (1997) as part of a hydrogeology study of the Tahoe basin. Data on the results of a ground water quality monitoring study done from 1990 to 1992 are presented. By multiplying mean nutrient concentrations from their ground water survey (N = 1.0 mg/L; P = 0.074 mg/L) and estimates of total annual ground water discharge to the lake (5.15 x 107 m^3), Thodal calculated "rounded estimates" of 60 MT for N-loading and of 4 MT for P-loading.

This accounted for 14 percent of the TN budget and nine percent of the TP budget. Nitrogen and phosphorus loading was assumed to be in the dissolved form (Thodal 1997).

Shoreline Erosion—The process of shoreline erosion and its quantitative importance to the nutrient and sediment budgets of Lake Tahoe have received very little attention. However, the importance of shoreline erosion has been highlighted in recent years as a result of high lake levels and strong sustained winds that altered some of the west shoreline by many feet. A preliminary estimate of the order-of-magnitude contribution of this process is presented here, with emphasis that additional studies must be performed before any action is based on these rough numbers.

Quantification of the contribution of shoreline erosion to the nutrient budget of Lake Tahoe requires two components: the concentrations of nitrogen and phosphorus associated with shorezone soils and the amount of material lost to the lake. In response to the former need, a pilot study was conducted (Hackley, S. H., B. C. Allen, and J. E. Reuter, University of California, Davis, unpublished data 1998) to determine a first-order estimate of N and P concentrations in backshore and shorezone sediment samples. This work was performed between July and September 1998 at Carnelian Bay, Lake Forest, Homewood, Sugar Pine Point, Pope Beach, and a site near Sand Harbor (TRG, unpublished). Thirty individual sediment sections, ranging from 0 to over 250 cm in depth, were analyzed. This work is ongoing; however, a continuance of this research at the pilot study level is unlikely to be sufficient to calculate adequately nutrient loading from this source.

The amount of shoreline eroded each year has not been quantified nor, even roughly estimated (Smith 1999). With this understanding, a rough estimate that represents a guess may later form the basis for a more comprehensive estimate. This estimate is needed for a number of reasons, including refining the nutrient budget and the extent of shorezone sediment loss. That stated, assuming that 55 percent of the lake's 113-km shoreline is subject to erosion and that on average, a cross-section with an area of 5 cm x 3 cm (0.0015) to 8 cm x 4 cm (0.0032 m^2) is lost from each kilometer of erodable shoreline, then on the order of 100 to 200 m^3 of material may be lost to the lake in a year. Over 10 years this would amount to 1,000 to 2,000 m^3 of shoreline sediment. Using a sediment density of 2.5 g/cm^3, this amounts to 2,500 to 5,000 MT of material during that 10-year period. Furthermore, it was assumed that once every 10 years, a very large erosion event results in an amount of erosion equivalent to that expected in an entire year. Under these circumstances, during this hypothetical 11-year period, there would be [e.g., 2,500 MT + 2,500 MT]/11 years, or approximately 450 to 900 MT of shoreline material eroded per year.

Using the field concentrations measured in the summer of 1998 (see above) the average ratio of TP:TSS was estimated at 0.0007. Concentration of total-P per unit of wet sediment in a single sample ranged from a high of 0.0013 to a low of 0.00003 g TP per g sediment. The mean values for TP per g of wet weight sediment at the sampling sites were within a factor of 2, ranging from 0.00041 to 0.00098. The exception to this was Pope Beach, which was very low in TP, 0.000068 g TP per g of wet weight sediment. Applying a mean TP concentration of 0.00068, a total-P load of 0.3-0.6 MT was calculated.

Sediment total-N concentrations measured by TRG in 1998 ranged from 0.00005 to 0.003 g TN per g sediment, with a mean of 0.0011 g TN per g sediment. TN between locations was more variable than for TP, with a range of 0.00025 to 0.00284 g TN per g of wet weight sediment. Again, the Pope Beach samples were much lower at 0.000084 g TN per g of wet weight sediment. Applying this to the calculation of total-N entering the lake via shoreline erosion resulted in an estimate of 0.5 to 1.0 MT. Note that these calculations depend on estimates of actual erosion shoreline erosion rates, which are extremely rough in this discussion.

Additional Considerations—Three sources of nutrients to Lake Tahoe that deserve special attention include sewage effluent, fertilizer application, and marina dredging. A body of knowledge based on research in the Tahoe basin exists for these three point sources. From a management perspective, these sources are less ambiguous than surface runoff, they can be readily identified and measures can be adopted for their reduction. Indeed, an early success at Tahoe in reducing nutrient loading to the lake was the use of scientific research and monitoring data to justify the cessation of sewage disposal within the basin and to the lake.

With increased population came the

problems of waste disposal. Populated areas first utilized septic tanks and leach fields, then more sophisticated secondary treatment systems, and finally a tertiary waste treatment facility managed by the South Lake Tahoe Public Utility District. As nutrient loading and lake clarity gained in public concern, introducing treated wastewater back into the lake was found to be inadvisable. Hence, sewage began to be exported from the basin beginning in 1968. Initially, some efforts were directed toward wastewater reuse. One pilot program sprayed effluent onto fields near Heavenly Valley. Five years after termination of this program, Heavenly Valley Creek was found to be discharging about 60 times more nitrate into Lake Tahoe than did Ward Creek, which received no effluent irrigation (Perkins et al. 1975; Goldman 1989). Old leaky septic tanks remain an uncontrolled potential source of nutrients that still could be affecting ground water (Loeb and Goldman 1979).

Historical and current use of commercial N and P fertilizers in the basin also is of concern. The fertilizers have been applied predominantly to ski slopes and large turf areas, such as parks and golf courses. Although no longer used to "harden" snow at ski areas, the long-term ramifications of this past practice remain unknown. Nutrient discharge from fertilizing golf courses and other turf areas is largely unknown. However, turf grass has been well documented to be highly efficient in the utilization of N and P. Fertilizer trials were conducted by the University of Nevada, Reno, in the mid- to late 1970s on several Sierra Nevada golf courses, including Incline (Gustafson and Miller, unpublished). Based on these findings, an N application of about 20 kilograms per 1,000 square meters per year of actual N would be sufficient to meet plant uptake without excess application. Properly managed, turf areas should function similarly to wetland and riparian zones in their ability to take up nutrients and to filter sediments. Loeb (1986) estimated that application of fertilizer within the Tahoe basin is significant. Approximately 26 to 28 MT of P are applied to basin soils each year by golf courses, homeowners, and others. These estimates were made on the basis of land use data and, according to Loeb, were similar to projected values made in an earlier study by Mitchell and Reisenaur (1974). While both these studies focus on fertilizer application, a quantitative understanding of effective loading to ground water or surface waters from this source does not take into account the nutrient budget. However, LTIMP sampling by the USGS on Edgewood Creek, Incline Creek, and the Upper Truckee River includes areas of golf course impact. The possible effects of this source will be part of the more detailed USGS-TRG report on the historical LTIMP stream database.

For many years the contribution of marina dredging to the nutrient load of Lake Tahoe was unknown. Hackley et al. (1996) conducted an extensive study of this issue from 1992 to 1994. Highlights from this work include the findings that considerable variability exists in the nutrient content of sediments between marinas, within a single marina, and within different layers of marina sediments. Raw sediment total-N or total-P were not good predictors of the level of soluble nutrients during elutriate tests. On the order of one to six percent of TP released to lake water during the elutriate testing was determined to be biologically available-P (BAP), as determined by chemical testing.

Field monitoring done around a horizontal cutter hydraulic dredge in Lake Tahoe showed that surface plumes were detectable quite a distance from the dredge itself (8-60 m) but that the highest concentrations of turbidity and nutrients were localized within 3-6 m of the dredge. It was not uncommon for concentrations of nutrients and turbidity at the dredge in the lake to be turbidity 10 to 20 NTU, total dissolved-P 10 to 30 μg/L, total-P 40 to >100 μg/L, nitrate 10 to 20 μg N/L, ammonium-N 25 to >50 μg/L, and TKN 200 to 500 μg/L. The mechanical dredging methods (e.g., excavator, clamshell, and dragline) had relatively high sediment resuspension.

The loading of N and P directly to the lake from dredging operations from a given marina was estimated to range from less than a single kilogram to tens of kilograms. These loads are comparable to other inputs from human activities. For instance, release of five kg of TN or TP was calculated to be roughly equivalent to the load in urban runoff from five acres of medium-developed residential or two to three acres of tourist-commercial property.

Summary of Inputs—The summary values presented below represents an initial estimate at quantifying the nutrient sources to Lake Tahoe. Depending on the amount and form of precipitation, individual water years will differ. Efforts are underway to provide estimates of both interannual and measurement variation to these values (Reuter, unpublished).

Our estimates suggest that approximately 17 MT, or about one-third of the TP load, is in the form of soluble-P and is immediately available for biological uptake. Values of this magnitude are not uncommon in the scientific literature (Reckhow and Chapra 1983; Hatch 1997). While it is important to understand the sources and process that render phosphorus available for algal uptake, it is noteworthy that many of the empirical models developed for lakes to relate phosphorus loading to trophic status or algal biomass are based on total-P (Reckhow and Chapra 1983). Studies are underway, but more are needed to elucidate the factors controlling transformations between the TP and soluble-P pools. This research must look at both watershed and in-lake processes.

The results at this time clearly suggest the importance of direct runoff from urban areas and highlight the need for additional study in this area. As restoration projects are targeted and adaptive management proceeds, it will be very helpful to have more detailed data on the specific sources of nutrients within each of the major categories discussed above. Restoration should give priority to those areas that contribute most to the nutrient loading budget.

INPUTS	**Nitrogen** (MT)	**Phosphorus** (MT)	
	Total	Total	Soluble
Atmospheric deposition	233.9 (56%)	12.4 (27%)	5.6
Stream loading	81.6 (20%)	13.3 (29%)	2.4
Direct runoff	41.8 (10%)	15.5 (34%)	5.0
Ground water	60 (14%)	4 (9%)	4
Shoreline erosion	0.75 (<1%)	0.45 (1%)	No Data
Total	**418.1**	**45.7**	**17.0**

Losses—As discussed in much further detail as part of Issue #3 (Mass Balance Considerations), Heyvaert and Reuter (TRG, unpublished) have found that nutrient sedimentation losses to the bottom of Lake Tahoe are 401.7 MT for total nitrogen and 52.8 MT for total phosphorus. These numbers agree remarkably well with the independent loading estimates given above. This close agreement gives increased confidence that the loading rates are representative.

Characteristics of Nutrient Loading in Lake Tahoe Tributaries, over Daily, Seasonal, Annual and Interannual Time Scales—with Emphasis on Phosphorus

Prior to 1980, tributary nutrient loading was monitored as part of basic research, as part of existing, albeit limited, water quality and streamflow monitoring, or as part of specific project studies, many of which were focused on highway cut-slope and discharge. By the late 1970s, these programs were no longer of sufficient scope or organized in such a manner as to provide the extensive database needed for land use planning and watershed management. In 1979, the LTIMP was established to meet these growing needs. LTIMP now consists of 10 to 15 federal, state, and local agencies.

Nearly 20 years of data from LTIMP has been used for many purposes, including erosion control planning, capital improvement construction projects, environmental policy, community growth planning, and basic research support. State and federal planning and enforcement agencies must base their decisions on data that will withstand the most careful scrutiny. Long-term monitoring of the lake and its tributary streams, as presently accomplished by the LTIMP program, is required as part of the adoption of the Basin 208 Plan.

LTIMP Tributary Monitoring

Sampling Design and Schedule—The basic, long-term tributary monitoring under LTIMP is currently operational on ten of the basin's 63 tributaries at primary sites where sampling is done near the point of inflow to Lake Tahoe. These streams include five in California (Ward Creek, Blackwood Creek, General Creek, Upper Truckee River, and Trout Creek) and five in Nevada (Edgewood Creek, Logan House Creek, Glenbrook Creek, Incline Creek, and Third Creek). However, LTIMP includes an additional 22 upstream sites on these tributaries, plus First, Second, Wood, and North Logan House Creeks. The reader is referred to excellent summaries of the LTIMP stream monitoring program by Rowe and Stone (1997) and Boughton et al. (1997).

Estimated runoff volumes from each of the 63 tributaries and for each intervening zone is given in Marjanovic (1989). The watershed coverage that drains into LTIMP streams comprises just under 50 percent of the total basin area and slightly greater than 50 percent of the total tributary runoff. The Upper Truckee River alone contributes 24 percent of the total tributary flow. Snow Creek in California was part of the LTIMP sampling design between 1980 and 1985, but it is no longer monitored.

The LTIMP streams are monitored by the USGS and TRG. TRG performs nutrient chemistry, and the USGS analyzes sediment. Field measurements include instantaneous and total discharge, specific conductance, and temperature. Over the period of record, the following forms of phosphorus and nitrogen have been measured: nitrate (+nitrite), ammonium, TKN, dissolved Kjeldahl-N (DKN), SRP, total reactive-P (TRP), total hydrolyzable-P (THP), dissolved hydrolyzable-P (DHP), total dissolved-P (TDP), TP, total biologically available iron (BAFe), and dissolved BAFe. Since 1994, nutrient analysis routinely includes nitrate, ammonium, TKN, SRP, TDP, TP, and total BAFe. Typically, 30 to 50 samples are taken each year representing stream hydrology, precipitation, and surface runoff events. Samples are collected with a depth-integrating sampler and are mixed in a churn splitter. Samples for dissolved P analysis are filtered on-site through 0.45 μm membranes. Water samples for SRP, TDP, and TP raw stream water are stored at 4˚C for transport and storage at the laboratory until analysis. Detailed LTIMP laboratory standard operating procedures and quality assurance/control protocol can be found in Hunter et al. (1993). Hatch (1997) provides details on specific methodologies used to measure P concentrations.

Three important milestones exist for the LTIMP tributary monitoring activities. The first milestone was its inception in Water Year (WY) 1980 (October 1979 to September 1980). At that time only Ward Creek, Blackwood Creek, Trout Creek, Upper Truckee River, and Third Creek were sampled. By WY 1981 this was expanded to include General Creek and Snow Creek. The second milestone was in WY 1988 when the number of stations in Nevada was increased as the USGS Carson City extended its activities in the Tahoe basin. By 1991 all of the 10 current stations were in operation. Because of funding difficulties, only Ward Creek, Blackwood Creek, General Creek, and the Upper Truckee River were sampled in WY 1986 and WY 1987. The third milestone was in the early 1990s when the basic LTIMP tributary program was again enhanced to include multiple stations (a total of three per tributary) on Incline Creek, Trout Creek, Ward Creek, and the Upper Truckee River. This multiple station monitoring on these tributaries has been continuous since WY 1991.

Data for the LTIMP nutrient (and sediment) sampling is available from a number of sources. From WY 1980 to WY 1988 the TRG published a series of annual reports, but ensuing LTIMP budgets were significantly reduced, and support was no longer available to produce these reports. In calendar year 1994, the TRG submitted a data report to the Lahontan Regional Water Quality Control Board that summarized stream nutrient concentration and load calculations from WY 1989 to 1993. Since then, the TRPA produces an annual report that summarizes the nutrient loading data calculated by the TRG. The raw concentration data also is published in the water resources data reports issued by the USGS-Nevada. Research papers and technical reports on this topic are available from the USGS, the TRG, and the TRPA.

A Brief Description of LTIMP Watersheds—In addition to the following brief descriptions of the primary LTIMP watersheds, data characterizing all the Tahoe basin watersheds (e.g., drainage area, channel length, elevation ranges, and slope) are available from the USGS (Jorgensen 1978; Cartier et al. 1995).

Ward Creek on the west shore of Lake Tahoe is primarily underlain with volcanic soils scoured by glaciers. The watershed is bound within a steep-walled canyon, with extensive human development near the mouth. As with the other nine LTIMP watersheds, the Ward Creek watershed experienced heavy logging during the late 19th century (Leonard and Goldman 1982). The upper portion of Ward Creek's north fork contains a recreational ski operation.

The Blackwood Creek watershed (west shore) is primarily underlain by volcanic and surficial deposits. The watershed is largely undeveloped, except for housing within 0.5 km of the lake; however, past disturbance has included logging, gravel excavation from the streambed/streambank, grazing, and fire. Most roads in this watershed are unpaved and subjected to intensive recreational off-road vehicle use.

General Creek (west shore), adjacent to Blackwood Creek, has been considered a "control" watershed because it has remained relatively undisturbed due to its location within a state park. This watershed has the lowest road density of the nine LTIMP watersheds. The upper regions of this watershed are underlain by glaciated granite and are in the Desolation Wilderness Area. Lower watershed areas are primarily underlain by surficial deposits.

The Upper Truckee River (south shore) watershed has the greatest area and stream discharge of all Tahoe watersheds (Dugan and McGauhey 1974). The lower meadowland reaches of the stream are extensively developed with housing, roads, commercial/industrial areas, golf courses, and an airport (Leonard and Goldman 1982). The lower watershed is composed of deep alluvial soils, while the upper undeveloped reaches contain steep granitic soils with some volcanics at the south end.

The Trout Creek (south shore) watershed is immediately to the east of the Upper Truckee River, with two major subwatersheds of Cold Creek and Saxon Creek. The lower reaches of Trout Creek flow through flat meadowlands subjected to extensive human development, but the undeveloped upper watershed is composed of steeper gradients and mixed coniferous forests above 2,800 m (Leonard and Goldman 1982). A large ski resort covers a significant amount of the steeper watershed areas. Trout Creek and Upper Truckee River converge near the lake in the Upper Truckee Marsh, which was disturbed extensively by excavation and construction of a large housing subdivision/marina in the 1960s.

Logan House Creek (east shore) is relatively steep along its entire length. Primarily underlain by metamorphic and granitic rock, this watershed has the lowest road length and the smallest area of the nine LTIMP watersheds. The watershed is largely undeveloped, and, as with other watersheds on the east shore, it typically receives half the precipitation of the west shore due to a "rain shadow" effect.

Glenbrook Creek (east shore) is north of the Logan House Creek watershed and composed primarily of volcanic and decomposed granitic rock. The upper regions are steep and undeveloped, while the middle regions have extensive highway road cuts. The lower watershed area is relatively flat with light to moderate development. Glenbrook Golf Course is within this watershed.

The Incline Creek (northeast shore) watershed consists of mountainous canyons primarily underlain by granitic bedrock with scattered volcanic deposits. The upper parts of the watershed are forested subalpine bowls, while the lower sections are less steep and consist of alluvial wash deposits. Human development is extensive near the lakeshore, including residential and commercial structures, golf courses, and a ski resort.

The Third Creek (northeast shore) watershed is immediately west of Incline Creek and also has been subjected to extensive human disturbance, including two golf courses. Third Creek extends several hundred meters higher in elevation than Incline Creek, with the upper area consisting of a large subalpine bowl. The lower watershed is narrow and relatively steep. The Third and Incline Creek watersheds experienced heavy disturbance in the 1960s and 1970s while Incline Village was being constructed. The mouths of these two streams are less than 50 m apart. Third Creek was the site of a large snow avalanche above Highway 431 in February 1986.

Stream Phosphorus Concentrations and Transport

Phosphorus source/sink behavior is much more difficult to characterize than that for nitrogen. Although phosphate (PO_4^{-3}) is highly soluble and therefore quite mobile, it has a distinct propensity to become strongly attached to mineral and organic particulates. Consequently its mobility in watersheds is related to sediment transport. Dissolved P moving through the soil is affected by adsorption, desorption, and biological activity. Particulate P levels, on the other hand, changes with the condition of a stream channel and stream discharge. Recent research suggests that P also can form mobile complexes with mineral/organic colloids (Rhea et al. 1996; Harlow 1998).

Relations among Movement of Nutrients, Water, and Sediment

Incline Village Tributaries—Glancy (1988) published a report on streamflow, sediment transport, and nutrient transport at Incline Village from 1970 to 1973. That study was designed to develop a basic knowledge of fundamental hydrologic parameters within the Incline Village study area, to provide some local perspective on alleged or suspected basin-wide problems, to demonstrate the technical and economic feasibility of acquiring certain types of essential hydrologic knowledge, to launch a first approximation effort to obtain data on nutrient transport by streamflow, and to provide databases and knowledge to allow and encourage more detailed and efficient future studies. The discussion below was taken directly from that report.

The nutrient data used in Glancy (1988) came from previously published progress reports (Glancy 1971, 1973, 1976a, b). (A review of the sediment portion of this work is summarized later in this section.) The nutrient data for this study were purposely collected during times of intensive sediment movement to assess conditions during periods of potentially intense erosion. The sampling strategy was not intended to document seasonal or long-term changes. While much of the evaluation focuses on Third and Incline Creeks, data from a similar study for Glenbrook Creek (Glancy 1977) also are analyzed. The studies include a discussion of a number of forms of phosphorus and nitrogen (dissolved, particulate, and total), as well as sediment and hydraulic discharge.

The measured concentration ranges for the three streams were similar, albeit, with a few notable exceptions. Glancy concluded that the "tentative study-period trends of ammonium and ortho-phosphate suggest accelerated nutrient movement during early phases of urban development when effects of land clearing and road construction may have triggered higher-than-normal nutrient releases from freshly disturbed surficial earth materials." He goes on to state, however, that such an implication is tenuous because of insufficient data.

Nutrient movements near the mouths of Third and Incline Creeks were analyzed both graphically and by statistical regression. Plots of nutrient transport rates versus streamflow and sediment transport showed some apparent relationships. This level of analysis indicated that most nutrients moving to the lake tended to increase as flow and sediment discharge increased. However, Glancy noted that the overall poor graphical correlations between most nutrient forms, and either streamflow or sediment transport suggest that nutrient movement may be influenced by other factors.

The statistical evaluations performed were intended to supplement the graphical categorizations. Reliance on the linear regression analyses was downplayed because many of the relationships among nutrient, flow, and sediment transport were curvilinear rather than linear. The correlation coefficients indicated that nutrient movement correlates better with sediment transport than with streamflow. These observations support the widely held contention that erosion and nutrient transport to the lake are related. The fact that the correlations for the less developed Glenbrook watershed were better than for either Third or Incline suggested that the relationship between erosion and nutrient transport is better defined in minimally developed areas. However, as Glancy stressed, the numerically small correlation coefficients suggest that the relations between erosion and nutrient transport are probably quite complex.

Data for Third and Incline Creeks further showed that fine-grained sediment (<63 µm and thus finer than sand) correlates better with nutrients than does coarse-grained sediment (≥63 µm) in about two-thirds of the regression analyses. The regression equation exponents were larger for the relationships between fine-grained sediment and nutrients versus coarse-grained sediment and nutrients, perhaps implying that nutrient transport is more sensitive to the movement of fine-grained material. However, many of the correlations for both coarse- and fine-grained sediment were observed to be only slight, and caution should be exercised in interpreting these results.

Ward Creek—A comprehensive paper on nutrient transport in surface runoff within the Ward Valley watershed was published by Leonard et al. (1979). Along with Glancy (1988), this remains one of the most comprehensive peer-reviewed works on tributaries in the Tahoe basin. These two documents have provided significant background and intellectual guidance for not only LTIMP but for many of the current investigations into discharge, nutrient transport, and sediment transport in Tahoe's tributaries. Below, excepts from the extended abstract and conclusions from the Leonard et al. paper are reviewed.

TRG investigations of nutrient and sediment transport in Ward Valley began in 1971. LTIMP monitoring has been continual since WY 1980 and current UC Davis-TRG hydrologic and sediment transport modeling focuses on Ward Valley (Kavvas et al. 1998). Quantitative data on selected stream water parameters were collected and evaluated by Leonard et al. (1979) for the period from 1972 to 1975 at three stations on Ward Creek, two on the main upper tributaries, and one near the stream mouth. Comparable data were collected at a stream mouth station on adjacent Blackwood Creek in the third year. The parameters were initially selected on the basis of their importance in eutrophication of Lake Tahoe. Sampling schedule and methodologies were similar to the current LTIMP program in that this study served as the precursor to LTIMP.

Sediment and nutrient loading to Lake Tahoe from Ward and Blackwood Creeks reflects a history of soil disturbance and vegetation removal. Logging, fire, and stream channel diversion have been dominant perturbations. Precipitation throughout the watershed during a normal year was primarily snow, but annual patterns varied widely, and rainfall at any time of year can be important in sediment and nutrient transport. Water discharge and the flux of suspended sediments, nitrate, phosphorus, iron, and trace metals was dominated by spring snowmelt runoff from mid-April to mid-June. However, in 1974 heavy fall and summer rains accounted for a large percentage of the annual flux of sediments and nutrients in a total of only 14 days (this phenomenon has been observed in other years since this study but is not common). Spring runoff was characterized by distinct diel water discharge patterns. Similar but not coincident patterns were found to exist for sediments and nutrients, including nitrate but not soluble-P. The Ward watershed has 87 percent of the area of Blackwood but discharged proportionately lower quantities of sediment and nutrients in terms of comparable water yield per hectare. This contrast may be explained in part by the history of greater disturbance in Blackwood Canyon.

The principal source of suspended sediments in Ward Creek was streambank erosion in the lower reaches of the channel. The dominant form of inorganic-N was nitrate derived from precipitation, terrestrial N_2-fixation and the nitrification of organic-N in forest soils. As observed by Glancy for Incline and Third Creeks, organic-N dominated the total-N flux. Phosphorus and iron were almost entirely in particulate form; thus, their dominant periods of flux occurred during high flows and sediment transport.

Five Year LTIMP Review—In 1986, Byron and Goldman issued a report summarizing the first five years of LTIMP. Findings of climatic effects (precipitation and runoff) appeared to have a dominant influence on stream water quality. Variation in water discharge is known to have a confounding effect on studies of long-term changes in stream water quality. The dominance of strong seasonal, storm-related, and year-to-year variation in discharge patterns can result in large fluctuations in volume-weighted concentrations (Byron and Goldman 1986). The results of multivariate statistical techniques to remove the effects of water discharge showed that Blackwood and Trout Creeks had a significantly decreasing nitrate concentration over the period from 1976 to 1985. TP and TSS did not show significant trends over time, but this may have been related to the shorter data records for these constituents.

The improvement in Blackwood Creek nitrate concentration was attributed to the gradual stabilization of in-channel disturbance. The reduction of nitrate concentration in Trout Creek was a more uniform change from year-to-year. Land disposal of secondary treated sewage occurred in this watershed from 1960 to 1965. With continuous leaching over the years, residual storage of nitrate was hypothesized to be gradually depleted.

Multiple Watershed Scale

While nearly 19 years of data now exist for a few LTIMP streams, many did not enter the program until the late 1980s. The LTIMP stream data set is consistent from WY 1989 to WY 1998 for the nine streams described above. Hatch (1997) examined the LTIMP stream phosphorus database from WY 1989 through WY 1996. One objective of that study was to characterize the LTIMP stream P data set by examining and comparing the P concentration and load databases on watershed. The discussion below comes directly from Hatch (1997). These analyses are helpful in understanding 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.

Data Reduction—During WY 1995, TDP was assayed for all stream samples, along with TP and SRP (Hatch 1997). Subtraction of TDP from TP yields particulate P (PP), while subtraction of SRP from TDP yields dissolved organic P (DOP). Phosphate (PO_4^{-3}) is assumed to be estimated by SRP (dissolved inorganic P). These four operationally defined P fractions (TP, PP, DOP, and PO_4^{-3}) were examined only for WY 1995, due to minimal TDP analyses for the rest of the WY 1989 to 1996 period (typically only eight to 12 TDP assays per stream per year). Presentation of the entire WY 1989 to 1996 data set considered TP and PO_4^{-3} only.

The WY 1989 to 1996 period covered five years of drought (WY 1989, 1990, 1991, 1992, and 1994) and three wet years (WY 1993, 1995, and 1996). For comparison, the WY 1981 to 1986 period included two years of drought (WY 1987 and 1988) and six wet years (WY 1981, 1982, 1983, 1984, 1985, and 1986). The representativeness of the WY 1989 to 1996 data (eight years) must be interpreted in light of drought conditions common during this period. It is clear, however, that much of the interannual variability in stream nutrient loading is due to differences in annual precipitation.

Two common methods for calculating annual and monthly concentration means are unweighted and discharge-weighted averaging. Unweighted averaging involves adding all concentrations for a given period and dividing by the total number of samples. Discharge weighting sums the instantaneous concentration-discharge products for a given period, then dividing this number by the sum of all sampling event instantaneous discharges for the same period. Discharge weighting (Yaksich and Verhoff 1983) may be useful to normalize for differences in concentrations due to varying discharges between sampling periods on a single creek and between creeks with highly different discharge ranges. Discharge weighting also gives more importance to high discharge concentrations (Galat 1990). Lewis et al. (1984) assert that for highly variable discharge systems in mountainous areas, discharge weighting best represents the chemical constituents accumulated in proportion to discharge, more accurately reflecting the conditions of the receiving lake. Based on these considerations, the discharge weighting method of mean calculation is used in this study. Standard errors are calculated using the instantaneous concentration values.

P loads (mass per unit time) were calculated using the rating curve method for individual water years as follows:

$$\text{Log}(TP_i * Q_i) = a + b * (\text{Log } Q_i)$$

$$\text{Daily Load (kg)} = (Q_d^{\,b}) * (10^a) * 86{,}400 * (10^{-9}) * \exp(2.65 * \text{MSE}).$$

The first equation generates the regression constants a and b along with the mean squared error (MSE) using all TP_i (instantaneous TP concentrations) and Q_i (instantaneous discharges) for a given water year and stream station. The second equation uses a, b, MSE, and Q_d (mean daily discharge for a given day) to generate daily loads.

The daily loading equation uses an adjustment of 86,400 seconds per day and 10^{-9} kilograms per microgram. The "anti-logging" procedure in the second equation is corrected by exp (2.65 * MSE) to account for the fact that anti-logging results in the geometric mean rather than the desired arithmetic mean (Ferguson 1986). This technique was recommended by the USGS in the Tahoe basin to compute stream loads. Daily loads were summed for monthly and annual loads. TP, PP, DOP, and PO_4^{-3} loads for the present study were calculated using this rating curve method.

Annual Variation in Stream Phosphorus Loads and Concentrations--Phosphorus loads were dominated by the particulate-P fraction (PP), which comprised 56 to 94 percent of the WY 1995 TP load for LTIMP streams (Figure 4-1). Maximum PP loads were 6,824 kg/year for the Upper Truckee River, followed by Third Creek (4,618 kg/year), Blackwood Creek (3,569 kg/year), Trout Creek (2,565 kg/year), and Ward Creek (2,465 kg/year). Mean annual WY 1989 to 1996 TP loads (Table 4-1) also were dominated by the Upper Truckee River (3,364 kg/yr), followed by Blackwood Creek (1,927 kg/yr), Trout Creek (1,281 kg/yr), Ward Creek (1,250 kg/yr), and Third Creek (1,120 kg/yr). Mean annual TP loads for the remaining streams ranged from 9 to 560 kg/yr. Annual TP load variation increased as load increased.

With respect to the dissolved P fractions, the DOP contribution to TP load during WY 1995 ranged from three to 29 percent, with the largest DOP loads coming from the Upper Truckee River (1,806 kg/year), Trout Creek (781 kg/year), Blackwood Creek (655 kg/year), and Ward Creek (445 kg/year). PO_4^{-3} comprised three to 17 percent of TP load, with the largest loads from the Upper Truckee River (1,120 kg/year), Trout Creek (598 kg/year), Ward Creek (322 kg/year), and Blackwood Creek (291 kg/year). Annual WY 1989 to 1996 PO_4^{-3} loads were less variable than TP loads, although the relative order of ranking by LTIMP streams was similar (Table 4-2). The Upper Truckee River averaged the highest mean annual PO_4^{-3} load, with 451 kg/yr, followed by Trout Creek (249 kg/yr), Blackwood Creek (158 kg/yr), and Ward Creek (149 kg/yr). The remaining streams contributed 1 to 80 kg/yr PO_4^{-3} per year.

Mean annual, discharge-weighted P concentrations for LTIMP streams were largely present as PP, comprising 58 to 96 percent of the TP concentration in WY 1995 (Figure 4-1). The highest mean PP concentration was 544 µg/L for Third Creek, followed by Incline Creek (146 µg/L), Blackwood Creek (114 µg/L), and Ward Creek (103 µg/L). Standard deviations for PP in WY 1995 were similar in magnitude to the annual means (76 to 133 percent of annual mean). WY 1989 to 1996 TP mean

Table 4-1—Mean annual phosphorus parameters for LTIMP streams, Water Years 1989-1996. All concentration means are discharge-weighted. TP = total P, PO_4 = phosphate. Parentheses: standard deviation for loads, SEM for concentrations.

Stream	TP Load (kg)	PO_4 Load (kg)	TP Conc. (µg L^{-1})	PO_4 Conc. (µg 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)

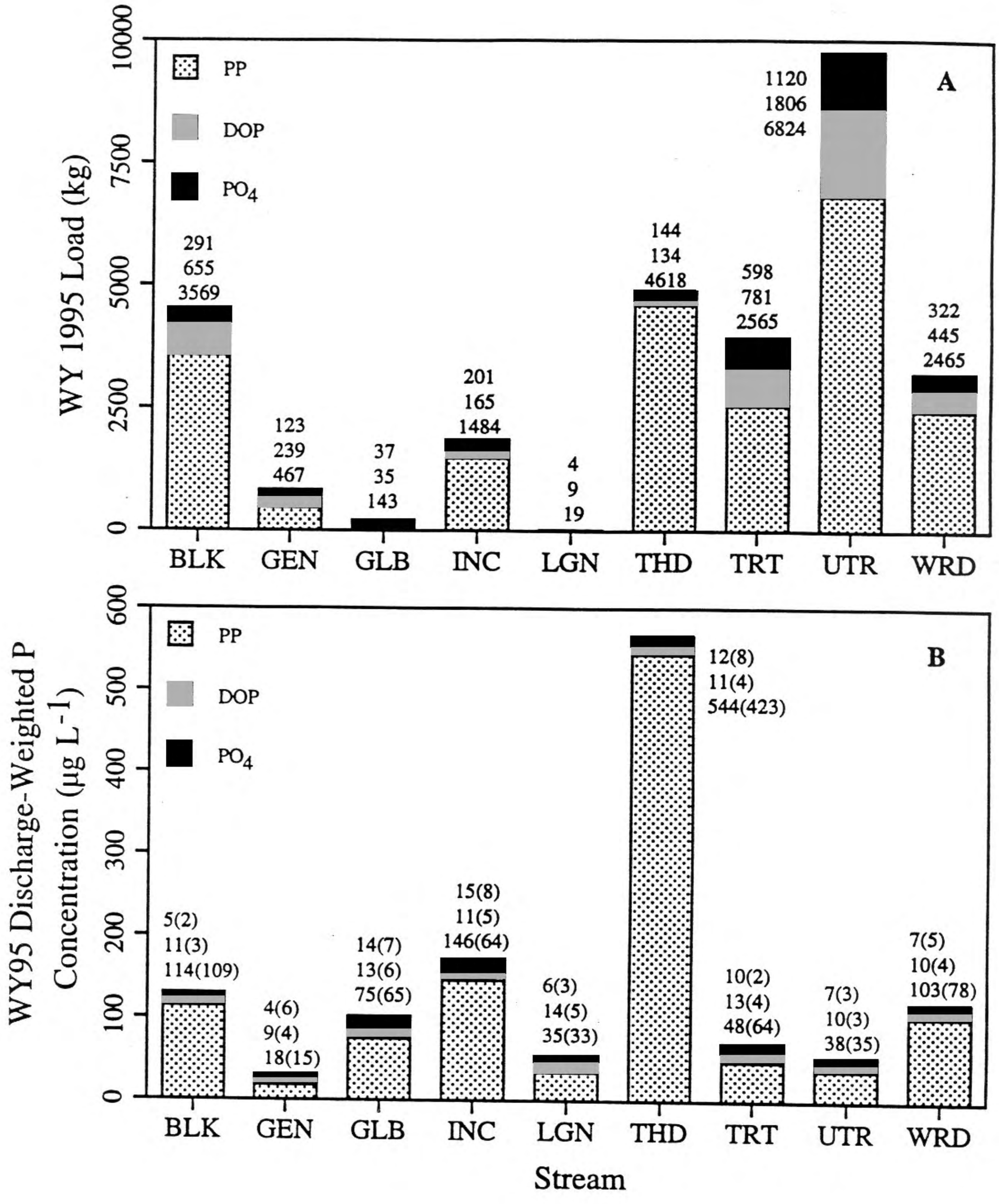


Figure 4-1—Concentration and total for PP, DOP, and PO4 at LTIMP stream mouth stations during Water Year 1995 (from Hatch 1997).

Table 4-2—Concentration and load rankings for LTIMP streams. Concentrations in μg L^{-1}, loads in kg (Hatch 1997). PO_4 = phosphate, TP = total P, PP = particulate P, DOP = dissolved organic P.

	WY95 Mean Annual Rankings[1]							
Stream	TP Conc. Rank	TP Load Rank	PP Conc. Rank	PP Load Rank	DOP Conc. Rank	DOP Load Rank	PO_4 Conc. Rank	PO_4 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 Rankings for the WY89-96 Period[2]							
Stream	TP Conc.	TP Conc. Rank	TP Load	TP Load Rank	PO_4 Conc.	PO_4 Conc. Rank	PO_4 Load	PO_4 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

Notes:
[1]Rankings according to values in Figure 2.
[2]Values represent the annual peak mean monthly values.

concentrations (Table 4-1) were also highly variable between the nine streams. Third Creek had the largest annual discharge-weighted TP concentration (220 μg/L), followed by Incline Creek (111 μg/L), Glenbrook Creek (101 μg/L), and Blackwood Creek (77 μg/L). Trout Creek, the Upper Truckee River, and Ward Creek had moderate TP concentrations (61 to 65 μg/L), followed by Logan House Creek (33 μg/L) and General Creek (24 μg/L).

For dissolved P discharge-weighted concentrations, DOP comprised two to 29 percent of the mean annual TP in terms of concentration, with levels ranging from 9 to 14 μg/L for all streams during WY 1995 (Figure 4-1). DOP standard deviations were lower than those for PP, ranging between 27 and 46 percent of the annual DOP mean. PO_4^{-3} contributed two to 14 percent of the TP concentration, with values of 15 μg/L for Incline Creek, 14 μg/L for Glenbrook Creek, and 12 μg/L for Third Creek. The remaining streams had PO_4^{-3} concentrations ranging from 4 to 10 μg/L for annual means. PO_4^{-3} standard deviations were smaller in magnitude than those seen for PP but comprised 20 percent to 150 percent of the mean annual PO_4^{-3} concentration. Annual means and standard deviations for DOP and PO_4^{-3} were similar for WY 1995. WY 1989 to 1996 PO_4^{-3} concentrations (Table 4-1) did not vary between streams on a mean annual basis (4 to 19 µg/L), and standard errors were small (≤ 1 µg/L). Glenbrook Creek and Incline Creek had the largest mean annual PO_4^{-3} concentrations of 19 µg/L, while General Creek and Logan House Creek had the smallest values at 4 µg/L. In general, annual TP and PO_4^{-3} concentrations for the WY 1989 to 1996 period were very similar to those for WY 1995.

Previous stream studies at Lake Tahoe from WY 1970 to 1973 on Glenbrook Creek, Incline Creek, and Third Creek also found TP concentration to consist of 83 percent, 83 percent, and 69 percent PP for these streams, respectively (Glancy 1977, 1988). Past studies on Ward Creek in the Tahoe basin showed that 84 percent of annual TP load was PP (Leonard et al. 1979), which is similar to the 76 percent value for Ward Creek in WY 1995. Relevant literature data from other high-mountain landscapes is rare. Leonard et al. (1979) found that PO_4^{-3} load comprised 11 percent of TP load for Ward Creek, which is very close to the 10 percent value for WY 1995. 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 breaking down stream organic material.

Monthly Variation in Stream Phosphorus Loads—Mean monthly P concentrations were highly variable for the LTIMP streams (Hatch 1997); monthly P loads, however, were greatest during the spring snowmelt. Using the Upper Truckee River during WY 1995 as an example, 77 percent of the PP load, 70 percent of the DOP load, and 73 percent of the PO_4^{-3} load occurred during the May-July period, while 92 percent of the PP load, 87 percent of the DOP load, and 89 percent of the PO_4^{-3} load occurred during the March-July period (Figure 4-2). During WY 1995, mean monthly PP loads ranged from 3 to 2,470 kg/month, DOP loads ranged

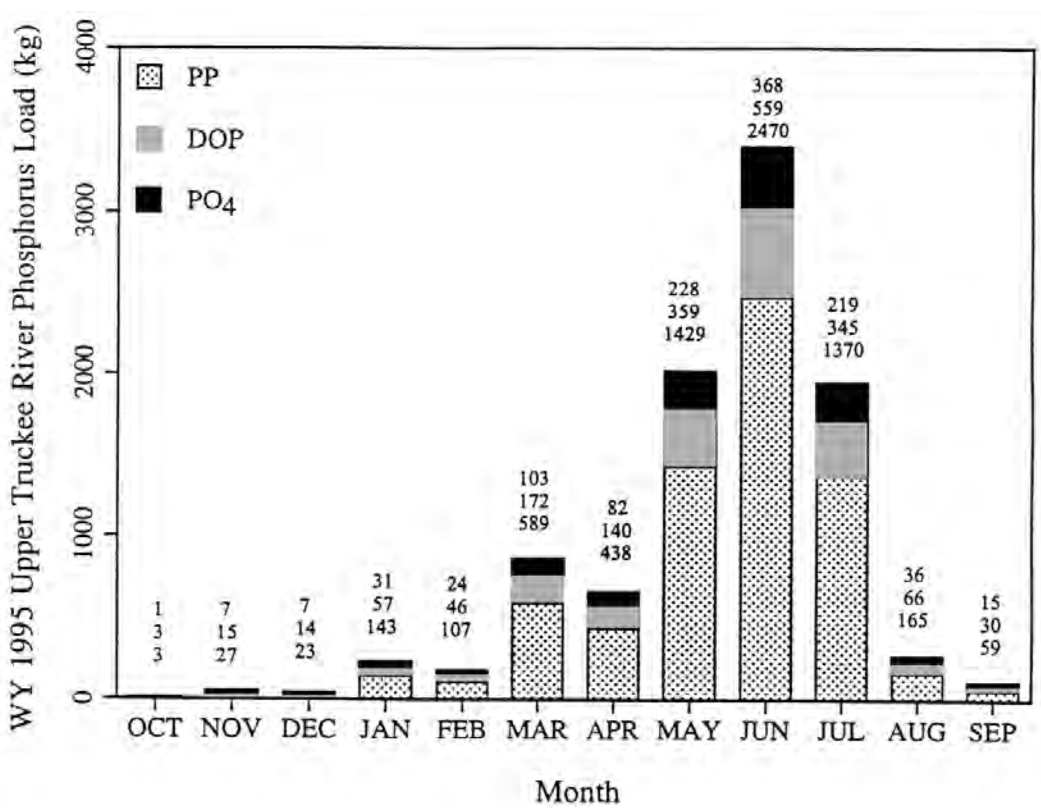


Figure 4-2—Seasonal distribution of PP, DOP, and PO4 at the mouth of the Upper Truckee River during Water Year 1995 (from Hatch 1997).

from 3 to 559 kg/month, and PO_4^{-3} loads ranged from 1 to 368 kg/month. As expected, mean monthly WY 1989 to 1996 TP loads also peaked at the height of the spring snowmelt (Hatch 1997). Phosphorus and suspended sediment concentrations also have been reported as being higher during the rising stage of stream flow, as the channel is flushed (Drivas 1986).

Concentration versus Load—Examining P concentration-load ranking differences on a monthly basis is best represented by using TP and PO_4^{-3} data from WY 1989 to 1996 (Table 4-2). Peak monthly loads during this period occurred during either May or June. The top three TP concentration rankings were occupied by Third Creek, Ward Creek, and Blackwood Creek. These streams ranked fourth, third, and second for TP loads. The Upper Truckee River, however, was ranked first with respect to TP load, but seventh with respect to TP concentration. The remaining streams ranked lower for both TP concentration and load. Mean annual PO_4^{-3} concentration rankings behaved differently than TP rankings. Although Glenbrook, Incline, and Third Creeks ranked as the top three PO_4^{-3} concentrations for the May/June period, these streams ranked near the bottom with respect to loads (8th, 6th, and 7th, respectively). The streams ranking first, second, and third in peak PO_4^{-3} loads (Upper Truckee River, Trout Creek, and Ward Creek) occupied the middle range of PO_4^{-3} concentration ranks at sixth, fourth, and fifth, respectively. The lowest ranked streams for PO_4^{-3} concentration (Logan House and General Creeks) occupied PO_4^{-3} load rank positions of ninth and fifth, respectively. As seen for the WY 1995 rank comparisons for annual P means, the WY 1989 to 1996 peak monthly mean comparisons also indicate that LTIMP streams with the highest P concentrations do not necessarily have the highest P loads, and vice versa.

Precipitation, Discharge, and Suspended Sediments—Precipitation, discharge, and suspended sediment analyses can be used to help explain the observed P variations in LTIMP streams. Precipitation in the Tahoe basin falls predominantly from October to March. Although most of this precipitation is snow, the large heat capacity of Lake Tahoe, which never freezes, creates a microclimatic effect. Estimates that 90 percent of Sierra Nevada precipitation is in the form of snow (Kattelmann 1990) may not agree with precipitation behavior at the near-lake elevations in the Lake Tahoe basin, which included large amounts of rain.

A significant relationship exists between annual precipitation (over each individual watershed) and annual areal discharge (liters/hectare) in LTIMP streams (Hatch 1997). This relationship occurred for both the inter-watershed WY 1989 to 1996 annual mean ($r^2 = 0.911$, $p < 0.001$, $n = 9$ watersheds) and the individual intra-watershed WY 1989 to 1996 means (all r^2 values ≥ 0.802, all p-values < 0.001, $n = 8$ water years per stream).

The net result of heavy winter precipitation is large stream discharges during the spring snowmelt, as indicated by P loads in Figure 4-2. Hatch (1997) demonstrated that peak monthly discharges during the WY 1989 to 1996 period occurred in May for the Upper Truckee River (211 x 108 L/month), Blackwood Creek (89 x 10^8 L/month), Ward Creek (66 x 10^8 L/month), General Creek (47 x 10^8 L/month), Incline Creek (11 x 10^8 L/month), Glenbrook Creek (3 x 10^8 L/month), and Logan House Creek (1 x 10^8 L/month). June discharge peaks occurred for Trout Creek (57 x 10^8 L/month) and Third Creek (14 x 10^8 L/month).

Suspended sediment is an important substrate for transport of P in stream systems (Logan 1987). There was a strong significant relationship ($p < 0.05$, $n = 7$ water years per stream) between intra-watershed annual TSS and TP concentrations (Hatch 1997) and also for WY 1989 to 1996 annual inter-watershed stream means ($r^2 = 0.84$, $p < 0.001$, $n = 9$ streams). A similar and even stronger correlation was seen between inter-watershed TSS and PP concentrations (r2 = 0.90, $p < 0.001$, $n = 9$ streams), although there were fewer measures of PP (approximately 8 to 12 per year per stream) than for TP (approximately 30 to 50 per year per stream). Kronvang et al. (1997) argue that as the proportion of PP to TP increases, there is a stronger association of both PP and TP with TSS. These relationships were also significant for intra-watershed annual means for all nine LTIMP streams, although outliers were present for Incline Creek, Logan House Creek, and Third Creek (Hatch 1997).

Relationships between TSS and DOP and between TSS and PO_4^{-3} concentrations were very poor, with few significant ($p < 0.05$) relationships for either intra-watershed or inter-watershed comparisons. The general lack of significant relationships between TSS and either DOP ($r^2 = 0.03$, $p = 0.633$, $n = 9$ streams) or PO_4^{-3} ($r^2 = 0.09$, $p = 0.430$, $n = 9$ streams) concentrations is not surprising because dissolved P by definition is not directly bound to particles; i.e., dissolved P passes through a 0.45 µm membrane.

Single Watershed Scale

Justification for Approach—While point sources of phosphorus (P) can be readily identified and sometimes controlled in efforts to halt lake eutrophication, nonpoint sources of P are closely linked to land use and thus are more difficult to quantify due to the physical scale of the problem (Omernik 1977; Correll 1977; Bordas and Canali 1980). In lieu of collecting an unwieldy amount of data on the scale of hundreds of hectares, an effective way to approach this dilemma has been to divide a watershed into several areas of differing land uses. For example, Dillon and Kirchner (1975) found that there was an increase in P export as one moved from forest to pasture to agricultural/urban watersheds. This supports the use of a single watershed as a conceptual framework for studying sources and transport of nonpoint source nutrient and sediment loading.

Hatch (1997) and Hatch et al. (1999) also analyzed the LTIMP database at the watershed scale using concentration and load values for phosphorus collected during WY 1991 to 1996 for Incline Creek (INC), Ward Creek (WRD), Trout Creek (TRT), and the Upper Truckee River (UTR). Three stations were monitored as part of LTIMP on each of these tributaries.

Site Description—Stream station INC3 is above human development, integrating the effects of forested subalpine bowls upstream. Station INC2 is farther downstream, representing the cumulative east branch of the creek. Between stations INC3 and INC2, the stream passes through residential development, a ski resort, and a golf course. Station INC1 is near the stream mouth, a few hundred meters downstream of INC2. The location of INC1 allows one to infer the effects of the west branch of Incline Creek, which passes through residential areas and part of a golf course.

Station TRT3 is high in the Trout Creek watershed, above areas of human development. This station integrates the effects of steep gradients and mixed coniferous forests above 2,800 m (Leonard and Goldman 1982). Station TRT2 is farther downstream, where the effects of human development on the stream first occur. Station TRT1 is in relatively flat meadowlands near the stream mouth within extensive development.

The Upper Truckee River is directly west of the Trout Creek watershed and has the greatest area and stream discharge of all Tahoe watersheds. Station UTR5 is immediately above the first instances of human development on the stream, although a small summer cattle grazing operation occurs several kilometers upstream. Steep granitic soils are present, with some volcanics at the south end. Station UTR3 is downstream of station UTR5 and represents an area under moderate development. Station UTR1 is near the stream mouth and sits on deep alluvial soils. Human development is heavy between stations UTR3 and UTR1 and includes housing, roads, commercial/industrial areas, golf courses, and an airport. The Upper Truckee River and Trout Creek converge near the lake in the Upper Truckee Marsh, which has been disturbed extensively from the development of a large residential marina.

Within the steep-walled Ward Creek watershed, station WRD3A is below the confluence of the two major upstream bowls, with minimal effects of development (one back bowl of a ski resort). Station WRD7A is farther downstream just below the last tributary confluence. Station WRD8 is near the lake within a region of significant human development.

Data Reduction Techniques—Using topographic divides for delineation, each stream was divided into three subwatersheds according to water quality station locations. Areal P loads for each subwatershed represent that area contributing P to a given gauging station. For example, the INC2 subwatershed includes all the area below station INC3 and its drainage but above the area that drains solely into station INC1. Areal loads (kg P/ha/yr) were calculated by subtracting upstream loads (kg/yr) from downstream loads (kg/yr), then dividing by the area of the watershed draining solely into the downstream gauging station.

Station Differences on the Annual Time Scale

The LTIMP data on multistation streams from WY 1991 to WY 1996 allow examination of P trends on an annual scale. This period was composed of below-average, average, and above-average precipitation years (Tahoe City precipitation [1931-1994 WY mean = 81 cm/yr]: WY 1991 = 58 cm, WY 1992 = 48 cm, WY 1993 = 105 cm, WY 1994 = 42 cm, WY 1995 = 154 cm, WY 1996 = 124 cm). Mean annual discharges increased in the downstream direction for each stream due to the cumulative contributions of tributary and ground water sources (Figure 4-3). Incline Creek stations had the lowest discharge values, with larger values for Trout Creek and Ward Creek. The Upper Truckee River had the greatest mean discharge.

P Concentration—Within-stream TP behavior was not the same for the four LTIMP streams (Figure 4-2C). TP concentrations increased downstream for Incline Creek, although INC1 and INC2 were not statistically different ($p>0.05$). Conversely, Trout Creek TP concentrations decreased in the downstream direction. The UTR1 TP concentration (43 μg/L) was statistically different from UTR3 (33 μg/L), but UTR1-to-UTR5 and UTR3-to-UTR5 TP concentrations were not statistically different. Despite the statistical difference between UTR1 and UTR3, the absolute magnitude of this difference was not great and may be of little practical significance. WRD7A and WRD3A had the same mean annual TP concentration, both being approximately half that recorded at the most downstream station at WRD8.

Analysis of TDP for the multistation streams during WY 1995 facilitated the calculation of PP, DOP, and PO_4^{-3} concentrations and loads. Particulate-P concentrations were not statistically different for INC2 and INC3, but both these stations were less than INC1. There were no statistical PP concentration differences between the three Trout Creek stations. There were also no statistical PP concentration differences between the two upper stations for the Upper Truckee River and Ward Creek, but the two upper stations were different from their respective stream mouth stations.

Mean annual PO_4^{-3} concentrations were quite similar for stations on the same stream. Incline Creek had the highest PO_4^{-3} values, ranging from 12 to 15 μg/L. Trout Creek had relatively intermediate concentrations at about 8 to 10 μg/L, while Ward Creek and the Upper Truckee River showed the lowest values at approximately 5 to 7 μg/L.

The WY 1995 data show within-watershed differences for DOP and PO_4^{-3} were minimal and most likely of little ecological significance in the streamflow. In Incline Creek, PO_4^{-3} concentrations were a few μg/L higher than DOP (11 to 15 μg/L vs. 10 to 12 μg/L), while just the opposite was recorded for Trout Creek. DOP for the Upper Truckee River and Ward Creek were noticeably higher than PO_4^{-3} (9 to 12 μg/L vs. 4 to 7 μg/L).

P Load—TP loads and PO_4^{-3} loads for the WY 1991 to 1996 increased in the downstream direction for all four streams. This condition reflects the fact that discharge, a major component of load calculation, always increased in the downstream direction. WY 1995 PP, DOP, and PO_4^{-3} loads also typically increased in the downstream direction for all streams. In general, the greatest loading increases occurred between the upper and middle stream stations for all three P fractions for each stream. For example, PP load increased greatly between TRT3 (649 kg) and TRT2 (2,078 kg), with a smaller increase between TRT2 and TRT1 (2,551 kg). An exception was the change for PP load between UTR3 (2,533 kg) and UTR1 (6,816 kg).

Subwatershed Phosphorus Characteristics—Stream P loads, not concentrations, are what actually affect Lake Tahoe phytoplankton as a whole. Adjusting stream loads by basin area assigns P loading values to specific areas of land. Because direct comparison of subwatershed areal

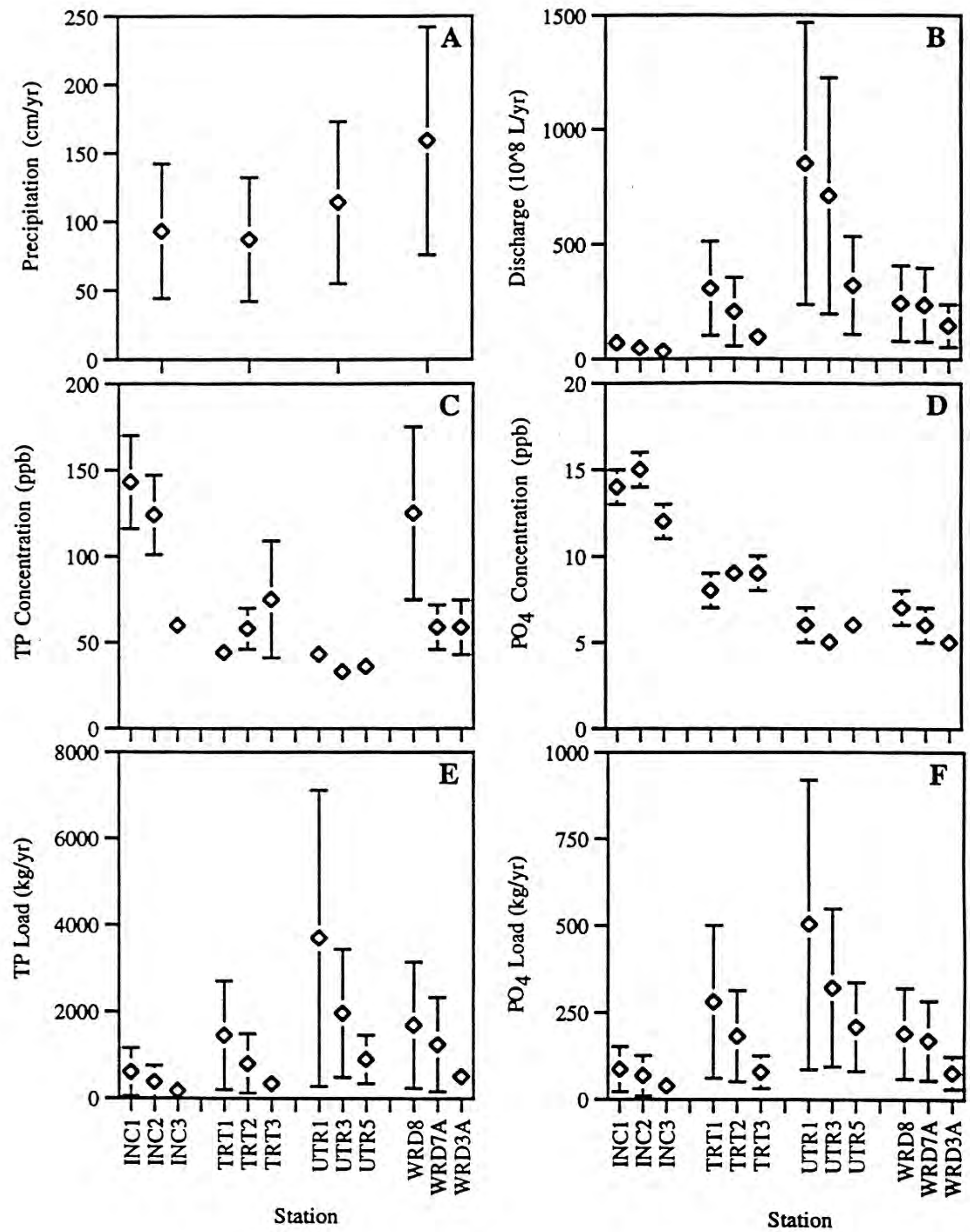


Figure 4-3—Annual precipitation, discharge, and phosphorus fractions for the multistation LTIMP creeks from Water Year 1991 to 1996 (from Hatch 1997).

P loads (kg/ha/yr) and discharge can result in spurious correlations due to a strong discharge-load relationship, it is more appropriate to compare areal P loads with precipitation.

Areal TP loads generally increased with increasing precipitation for the four LTIMP streams during the WY 1991 to 1996 period (Figure 4-4; note differences in axis ranges between creeks). The WRD3A (i.e., most upstream) subwatershed areal TP loads did not increase greatly with precipitation levels. Differences in areal TP loading between

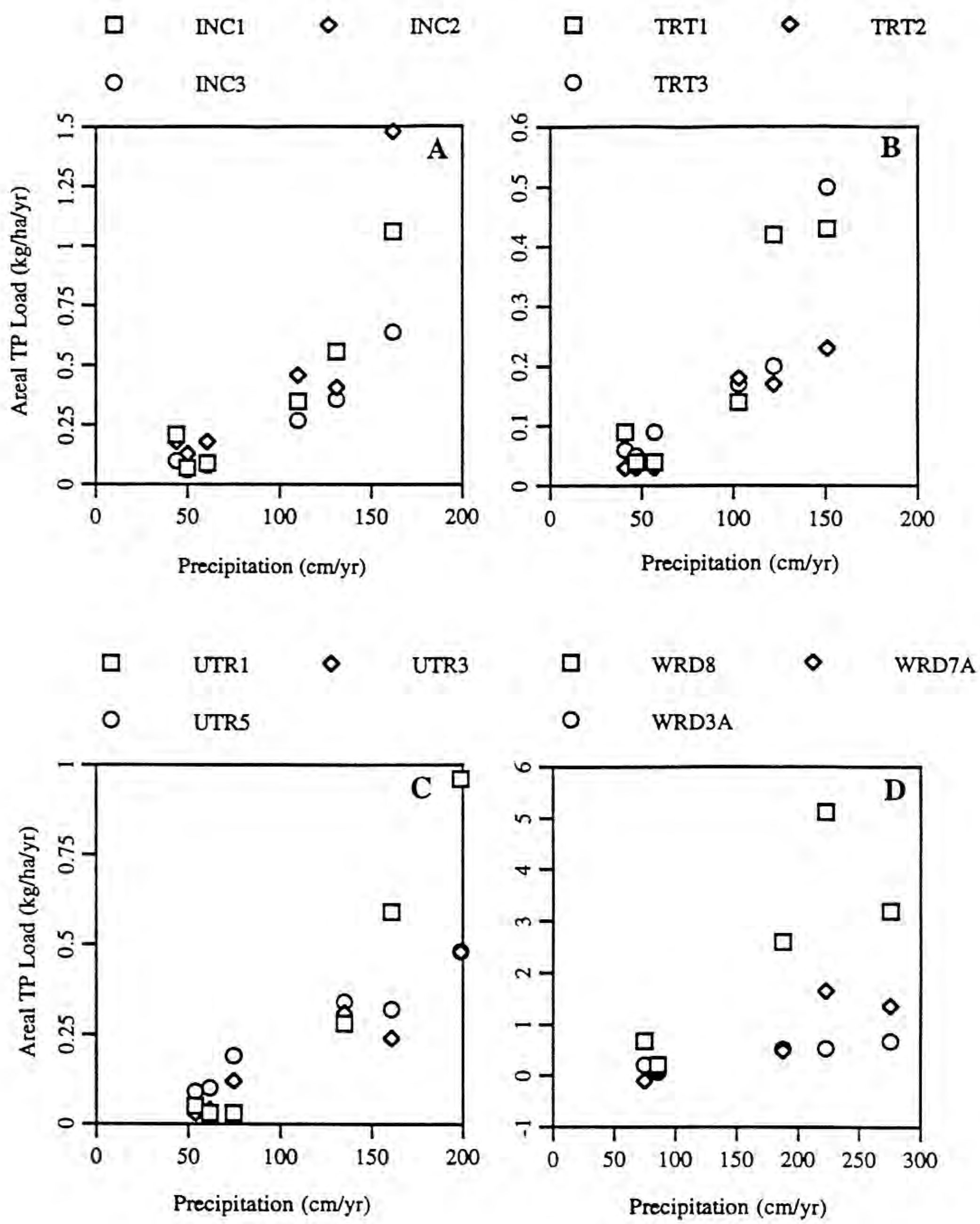


Figure 4-4—Relationship between areal TP load and precipitation for the subwatersheds defined by the multistation sampling design on four LTIMP creeks (from Hatch 1997).

subwatersheds on the same stream were minimal during relatively low precipitation years, but during high precipitation years obvious contrasts existed. For example, Incline Creek's areal TP loads were quite similar among the three subwatersheds when precipitation was around 50 cm/yr . However, at precipitation levels greater than 150 cm/yr there was a large difference among the three stations. This "threshold" precipitation value of approximately 150 cm/yr was similar for the Upper Truckee River and

Ward Creek but slightly different for Trout Creek (approximately 110 cm/yr).

There also appeared to be threshold precipitation values at which areal PO_4^{-3} load differences emerged between subwatersheds, but these values occurred at a lower level of precipitation than those seen for areal TP loads. Subwatershed areal PO_4^{-3} differences began occurring around precipitation values of 125 cm/yr for Incline Creek, 50 to 100 cm/yr for Trout Creek, 75 to 125 cm/yr for the Upper Truckee River, and 100 to 175 cm/yr for Ward Creek. Future data will most likely fill in the precipitation gaps and allow greater delineation of these precipitation thresholds.

According to Hatch (1997), instream and near-stream processes undoubtedly influence the P behavior observed in the four study streams. Stream PP sources, due in part to association with sediment particles and TSS, have been linked to streambank erosion. Leonard et al. (1979) suggested that streambank erosion in the lower reaches of Ward Creek was responsible for the large increase in PP between the mid-watershed and lower-watershed sampling stations. Work done on adjacent Blackwood Creek implies that 70 percent of stream TSS came from streambank and streambed erosion in low order channels, with the majority coming from the main channel and a much less amount coming from sheet/rill erosion next to stream channels (Nolan and Hill 1987).

Variation in Daily P Transport

Missing from stream studies at Lake Tahoe has been an assessment of how daily P transport varies, especially during the temperature-driven spring snowmelt cycle. In a study by Hatch (1997) and Hatch et al. (1999), P variability was assessed by conducting 24-hour sampling studies (once monthly) on three Incline Creek stations from May 1995 to March 1996. This analysis was necessary to understand the real-time variation of P because the hydrologic events that drive the movement of sediment-associated P from Tahoe streams to the lake occur on an hourly to daily time scale (Leonard et al. 1979).

Data Collection—Twenty-four hour (diel) monitoring took place during the first week of each month, from May 1995 through March 1996. Stations included INC3 (above human development), INC2 (representing the cumulative east branch), and INC1 located near the mouth (Figure 4-5). Sampling times for the sites during each diel study were at 11AM, 3PM, 6PM, 9PM, 12AM, 7AM, and 11AM. At each site the stream stage was determined by reading the staff gauge at the USGS gauge house. Sampling occurred during temperature-driven snowmelt and low-discharge conditions; no rain-on-soil or rain-on-snow events were sampled. A three-liter grab sample was taken in the main stream current. Particulate-P associated with different particle sizes was determined as sand-sized fraction of particulate-P (PP_{sand}), and silt- and clay-sized fraction of particulate-P (PP_{s+c}). Quality assurance procedures consisted of duplicates and spike recoveries, which were performed on 10 percent of the samples for a given analytical run. All sample analyses were within the LTIMP quality assurance tolerance limits (Hunter et al. 1993). Six P fractions were examined: TP, PP, PP_{sand}, PP_{s+c}, DOP, and PO_4^{-3}.

Station Differences on the Daily Time Scale

Diel Changes in P Concentration—The annual snowmelt runoff season was covered quite well by the Incline Creek diel studies. The effect of increasing discharge as one moves downstream from station INC3 to INC2 to INC1 was evident, as were the typical high discharges in May, June, and July.

Daily and seasonal diel behavior for the three Incline Creek stations indicates that the largest daily TP fluctuations coincided with the largest mean daily discharge (in WY 1995 this occurred in June). However, high mean daily discharges also occurred in July but without corresponding large values for TP. Hatch reported this behavior as indicative of the seasonal "first flush" phenomenon. Large quantities of P-bearing sediment appear to have been flushed from the stream during the initial high discharges of June, leaving less material readily available for transport in July.

PP was the dominant form of phosphorus during periods of high discharge. Mean monthly diel

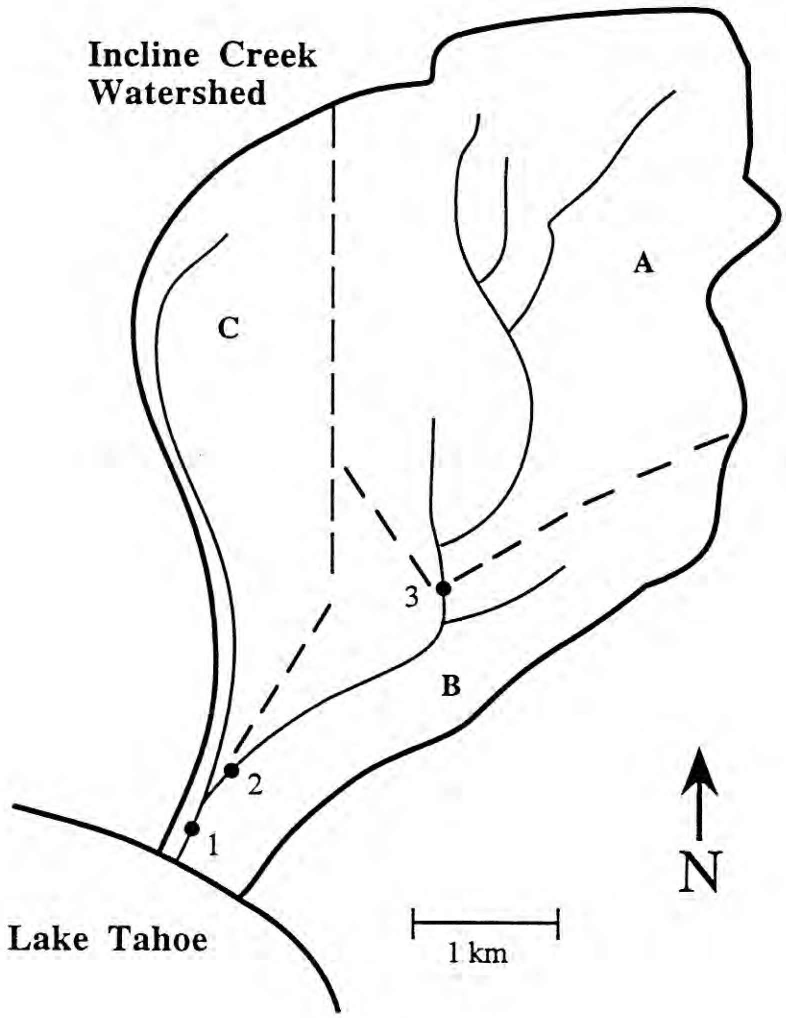


Figure 4-5—Diagram of Incline Creek watershed denotes location of three sampling stations and corresponding subwatershed drainages.

PP typically comprised 49 to 83 percent of the TP concentration at that time. PP concentrations for the June 1995 diel study fluctuated from 75 to 350 µg/L for INC1, 55 to 326 µg/L for INC2, and 40 to 210 µg/L for INC3. Peak PP concentrations were higher for both INC1 and INC2 than for INC3 during the May, June, and July studies, but PP values were similar for all three stations the remainder of the year (within 5 µg/L of one another). Leonard et al. (1979), working in Ward Creek, found that PP concentrations peaked around 250 ppb during May/June but remained below 10 ppb for the rest of the year.

The fluctuations in DOP concentration were not as great as those for PP, and the largest daily variations did not occur until August and September. At that time, mean diel DOP was 37 to 44 percent of TP. Peak DOP values at all three stations were nearly identical, at 10 to 30 µg/L. Throughout the study, never more than a 4 µg/L monthly mean DOP difference was found among the three Incline Creek stations. The elevated DOP levels in late summer and early fall are most likely due to peak summer production of stream periphyton exudates (Perkins 1976) and/or leaf-fall and in-stream litter processing.

Peak PO_4^{-3} concentration fluctuations were relatively small, with values ranging from 8 to 15 μg/L during the period of maximum discharge (i.e., June). PO_4^{-3} concentrations were greater than either PP or DOP during the November, January, and February studies, comprising 37 to 58 percent of mean diel TP concentrations. For each month from August 1995 to March 1996, PO_4^{-3} as a percentage of TP decreased in the downstream direction. This behavior was the opposite as that seen for PP, which increased its contribution in the downstream direction.

Relationship of P Concentration to Daily Discharge Cycle—The June 1995 diel study allowed for a more detailed examination of the relationship between P concentration and the daily snowmelt-driven discharge cycle. Peak discharges in Incline Creek at that time were observed at 9PM for INC1 (2,038 L/s), 6PM for INC2 (1,442 L/s), and 9PM for INC3 (1,333 L/s) (Figure 4-6). Although the exact time of peak discharge was probably not sampled, peak discharge was inferred to have occurred in the early evening during spring runoff as snowmelt water from upper portions of the watershed reaches the monitoring stations downstream (Hatch 1997). However, this conclusion may be valid for only Incline Creek. For example, peak snowmelt discharges for the Upper Truckee River generally occurs around 3AM due to the large watershed size and resultant time-to-concentration for discharge (Rowe 1999).

Maximum PP concentrations occurred prior to the observed peak in discharge at the mouth and upstream stations. At station INC2, both discharge and PP concentration peaked simultaneously at 6PM. INC1 displayed the largest changes in PP during the daily rising and falling hydrograph limbs, with INC2 and INC3 displaying smaller changes. PP appears to depend highly on discharge during the spring snowmelt for all three Incline Creek stations.

DOP concentrations ranged from 20 to 30 μg/L during the June diel study and were an order of magnitude lower than the observed PP concentrations. DOP concentrations were quite similar among the three stations, differing no more than 7 μg/L. Unlike PP, DOP concentrations continued to increase during the falling limb of the daily discharge cycle. Hatch et al. (1999) tentatively concluded that DOP did not directly depend on discharge. Ground water increases following the surface discharge peak may be possible sources of the increasing DOP, although ground water was not monitored.

PO_4^{-3} concentrations were quite similar among the three stations during June at approximately 10 μg/L. PO_4^{-3} remained relatively constant throughout the 24-hour period, implying independence from discharge.

Size Fractionation of Particulate P—Further insight into the large diel concentration fluctuations seen for PP during the period of maximum discharge was obtained by examining the behavior of PP_{sand} (particulate P associated with particles > 63 μm) and PP_{s+c} (particulate P associated with particles > 0.45 μm but < 63 μm, i.e., silts and clays). PP_{sand} displayed behavior similar to that of PP, with peak values occurring at 6PM (158 to 259 μg/L). Peak values for PP_{s+c} (54 to 83 μg/L) were much lower than those for PP_{sand} and were observed later in the diel period at 9PM. Peak concentrations increased in the downstream direction for both PP_{sand} and PP_{s+c}.

Stream hysteresis (changing relationship between phosphorus and flow over the diel period) varied according to P size fraction. For example, a counter-clockwise hysteresis was inferred for DOP concentration since DOP continued to rise as discharge decreased in the early morning hours. Walling and Webb (1980), using specific conductance, reported both clockwise and counter-clockwise hysteresis loops along different stretches of the same English stream system. These authors argued that this varying behavior was the result of differing source area chemical composition. Diel movement of hydraulic discharge and associated nutrients through the melting snowpack via ice lenses also may influence the hysteresis behavior of dissolved stream ions (Caine 1992) .

The differing hysteresis behavior for the PP_{sand} and PP_{s+c} fractions in Incline Creek may be explained by considering the physical conditions necessary to mobilize each fraction and the source of each fraction. Hatch et al. note that sand-sized particles require a higher velocity and shear stress

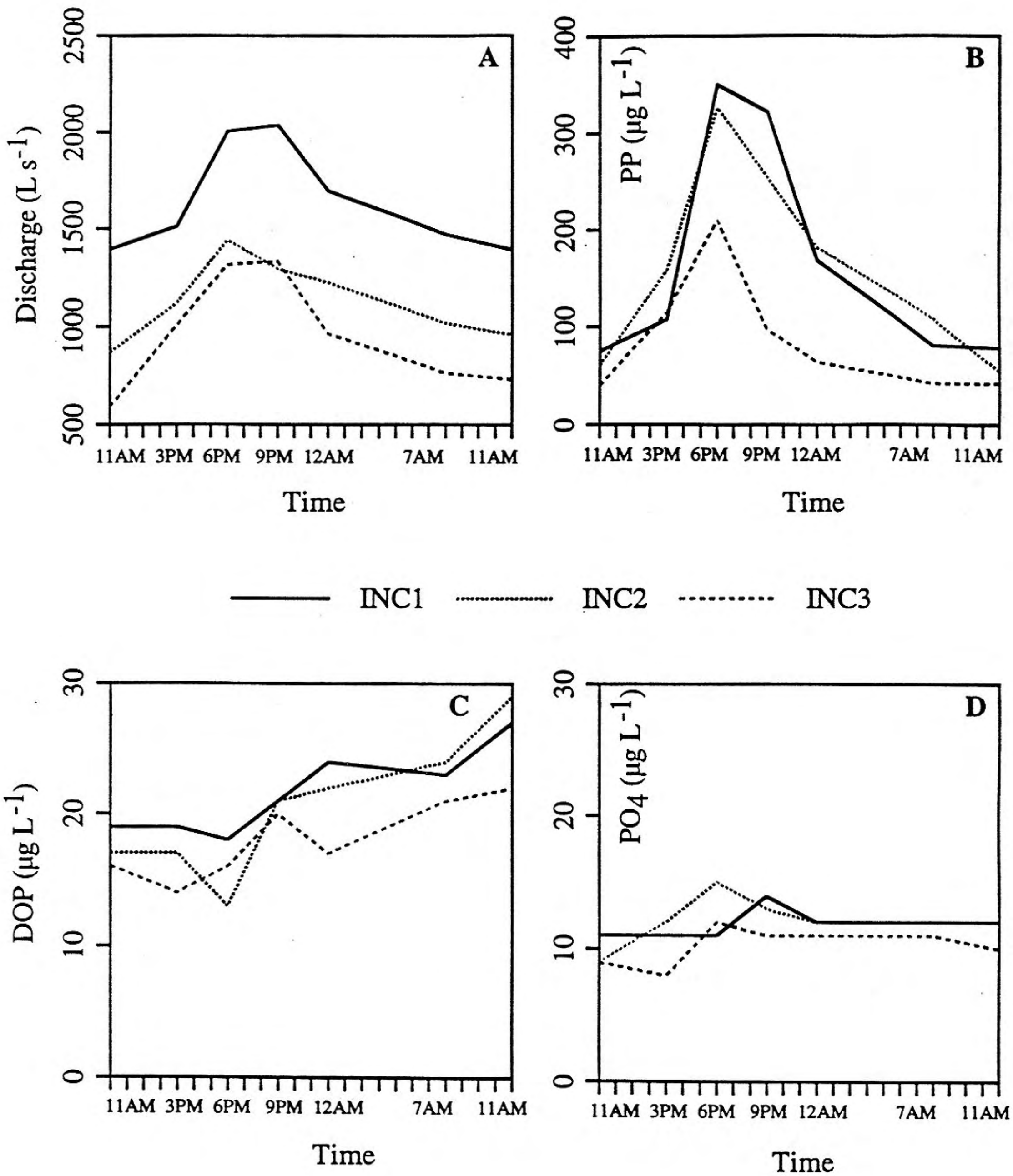


Figure 4-6—Diel pattern of discharge and phosphorus concentration at three stations on Incline Creek, June 1995 (from Hatch 1999).

to become entrained in flow than smaller-sized particles. Hence a threshold-like behavior in which significant amounts of sands are mobilized once a certain discharge is reached; may be displayed. For stations INC1 and INC2 this threshold appears to occur around 1,000-1,500 L/s. Once the flow threshold is reached and the sediment flushing occurs, significant sources of sand-sized particles may be exhausted, resulting in lowered sediment levels for a given discharge during the falling hydrograph limb (i.e., clockwise hysteresis).

Silt- and clay-sized particles require lower shear stress to become entrained in the flow. It is possible that the shear stress required to suspend and entrain these smaller particles in Incline Creek is present at all hours of the day during the daily snowmelt cycle. There was little fluctuation in PP_{S+C} over the 24-hour period, and PP_{S+C} increased with rising flows even at low rates of discharge. The counter-clockwise hysteresis seen for PP_{S+C} also may be the result of a nonstream channel source, possibly subsurface (Loeb and Goldman 1979). Very small particulates may move within the coarse soil matrix of the Tahoe basin (Rhea et al. 1996), so it is possible that the heightened PP_{S+C} levels seen on the falling hydrograph limb are due to subsurface sources of P, which reach a maximum after the peak stream discharge occurs.

Hatch et al. concluded that instream and near-stream processes both influence the P behavior observed in Incline Creek. Stream PP sources, due in part to association with sediment particles and TSS, have been linked to streambank and streambed erosion. Dissolved P concentrations in Incline Creek are most likely the result of equilibrium processes between stream water, stream suspended sediments, and stream bottom/bank sediments (Meyer and Likens 1979). Incline Creek showed relatively small changes in PO_4^{-3} between stations. The extent to which stream bottom and suspended sediment P retention is influencing these similarities is unknown. Downstream subwatershed dissolved P contributions plus dissolved P from the upstream monitoring station may be offset by stream bottom P and suspended sediment buffering, resulting in similar dissolved P concentrations for the three Incline Creek stations. Stream bottom retention of dissolved P also was reported in Ward Creek (Perkins 1976; Leonard et al. 1979).

Colloids and Their Potential Importance to Nutrient Water Chemistry

Colloid nutrient transport also can play a significant role in organic and inorganic nutrients migrating to stream and lake ecosystems (Ryan and Gschwend 1990; Chin and Gschwend 1991; Qualls and Haines 1991; Backhus et al. 1993; Rhea et al. 1996). Lake Tahoe research in this regard is in its infancy. Rhea et al. (1996) investigated the presence and behavior of colloidal N and P in a Lake Tahoe subbasin before and after the application of a 10 cm/h one-hour artificial rainfall event. Colloidal rather than inorganic nutrient species were the dominant forms present in soil water extracts taken both before and after the artificial event (figures 4-7, 4-8, and 4-9). As a result of their findings, it is now apparent that colloidal nutrient forms must be considered a potential source of mobile nutrients in soils of the Sierra Nevada.

At the watershed scale, a number of factors, including geology, vegetation, and extent of erosion may affect the form and magnitude of phosphorus contained in tributary discharge. Harlow (1998) conducted a study in an undisturbed portion of Incline Creek to investigate the leachability of P from undisturbed soil cores taken from upland and riparian plant communities. No significant differences among plant communities for leachable inorganic ortho-phosphorus or dissolved organic/colloidal P were identified. Furthermore, no correlation was found between inorganic or dissolved organic/colloidal P concentrations in the leachate and any other soil properties, including oxalate extractable iron and aluminum. The median ratio of dissolved organic/colloidal P to PO_4^{-3} was 0.38, lower than that reported by Rhea et al. (1996). Although this study did not collect data on TP, several studies have indicated that the TP levels (which include both the digested and inorganic fraction) are typically significantly higher than the dissolved fraction alone (Leonard et al. 1979; Byron and Goldman 1989; Vaithiyanathan and Correll 1992; Hatch 1997). This is likely the case for the Incline Creek watershed as well. Harlow (1998) also identified a "delayed" inorganic phosphorus peak (figures 4-10 and 4-11) during leaching that was consistent with the findings of Marcus et al. (1998). Unlike other nonconservative nutrients, such as nitrate-N, the delayed phosphorus release could be significant when considering nutrient transport during longer duration snowmelt runoff events versus brief summer precipitation events. The transport of P through the riparian corridor and into the stream is in need of further investigation.

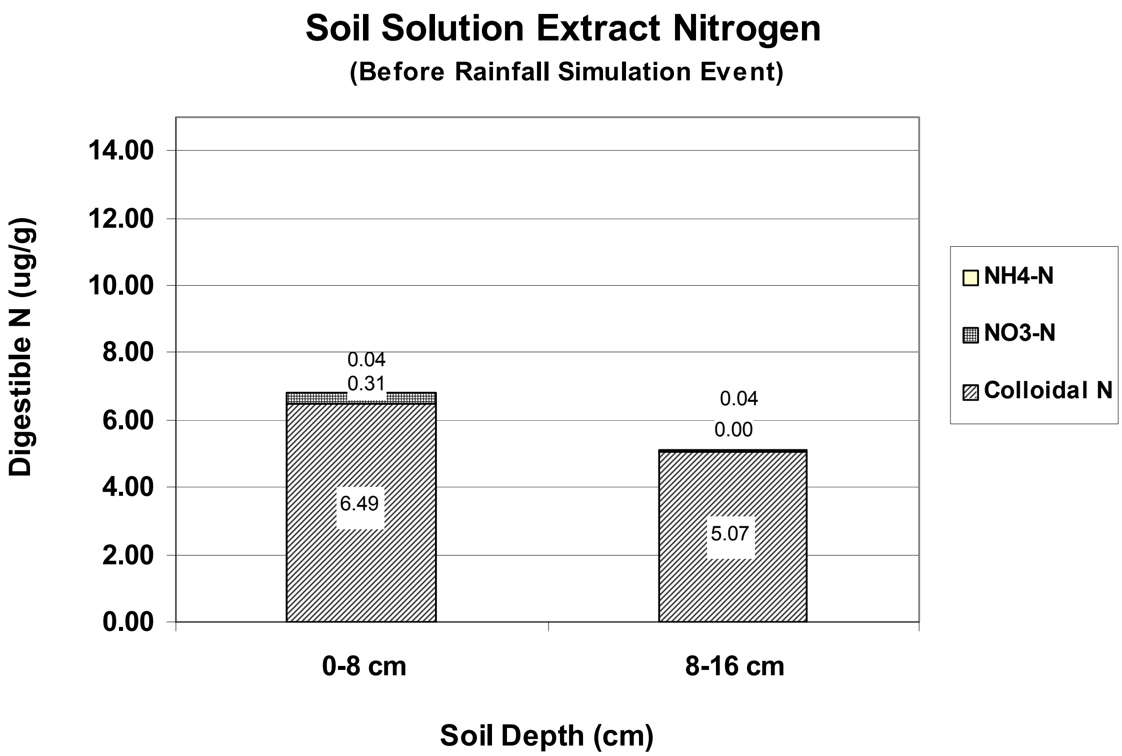


Figure 4-7—Water extractable inorganic and colloidal nitrogen from soil before artificial rainfall (from Rhea et al. 1996).

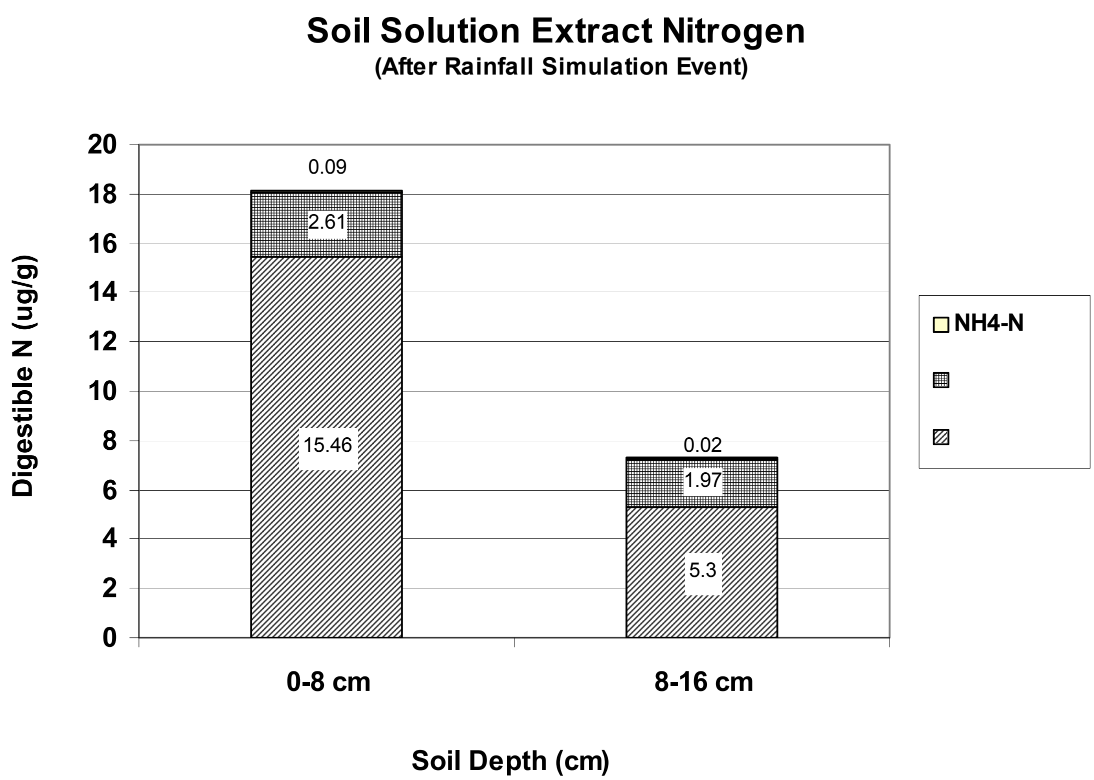
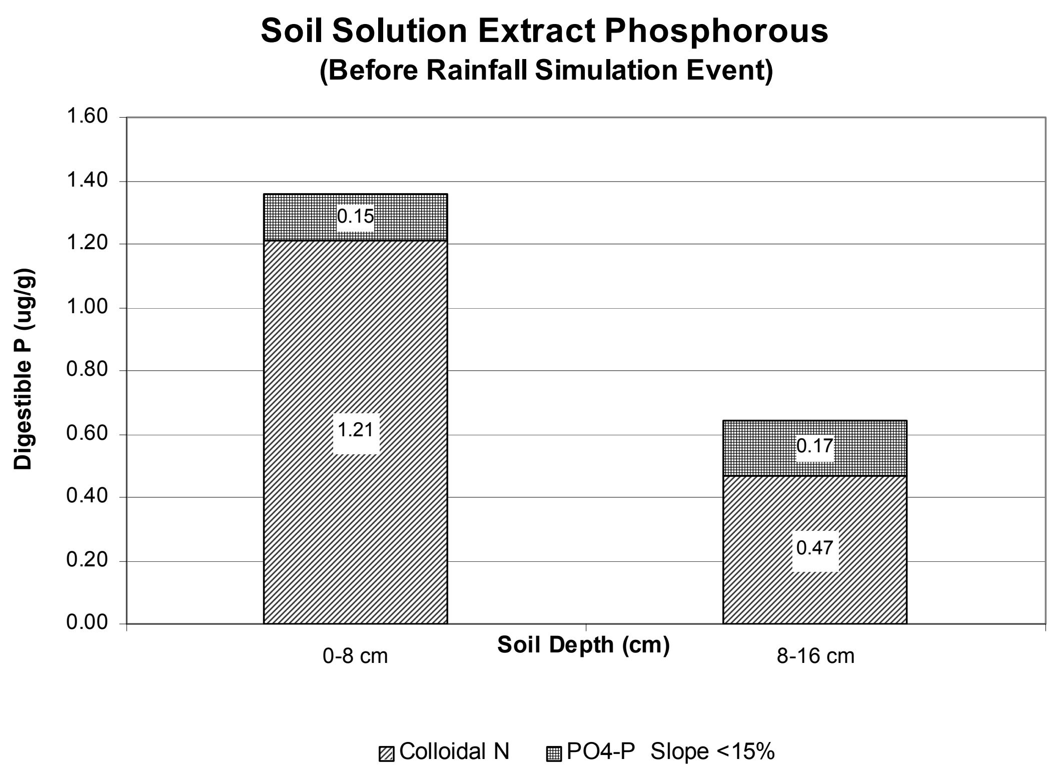


Figure 4-8—Water extractable inorganic and colloidal nitrogen from soil after artificial rainfall (from Rhea et al. 1996).



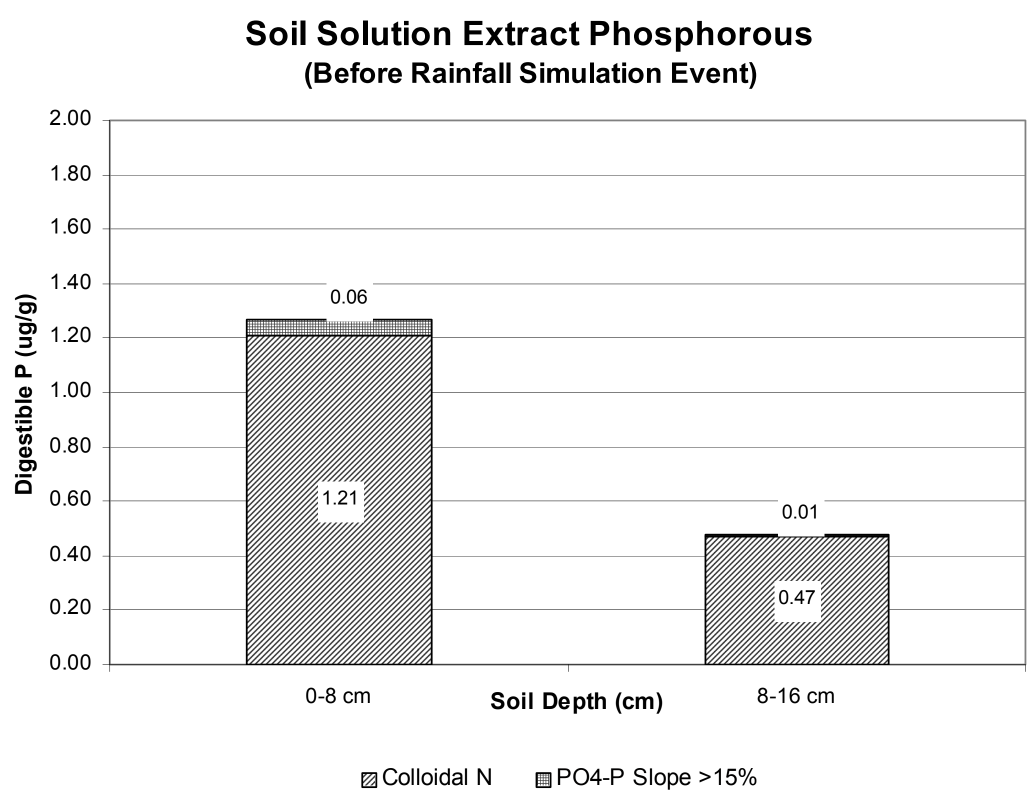


Figure 4-9—Water extractable inorganic and colloidal phosphorus from soil before and after artificial rainfall (from Rhea et al. 1996).

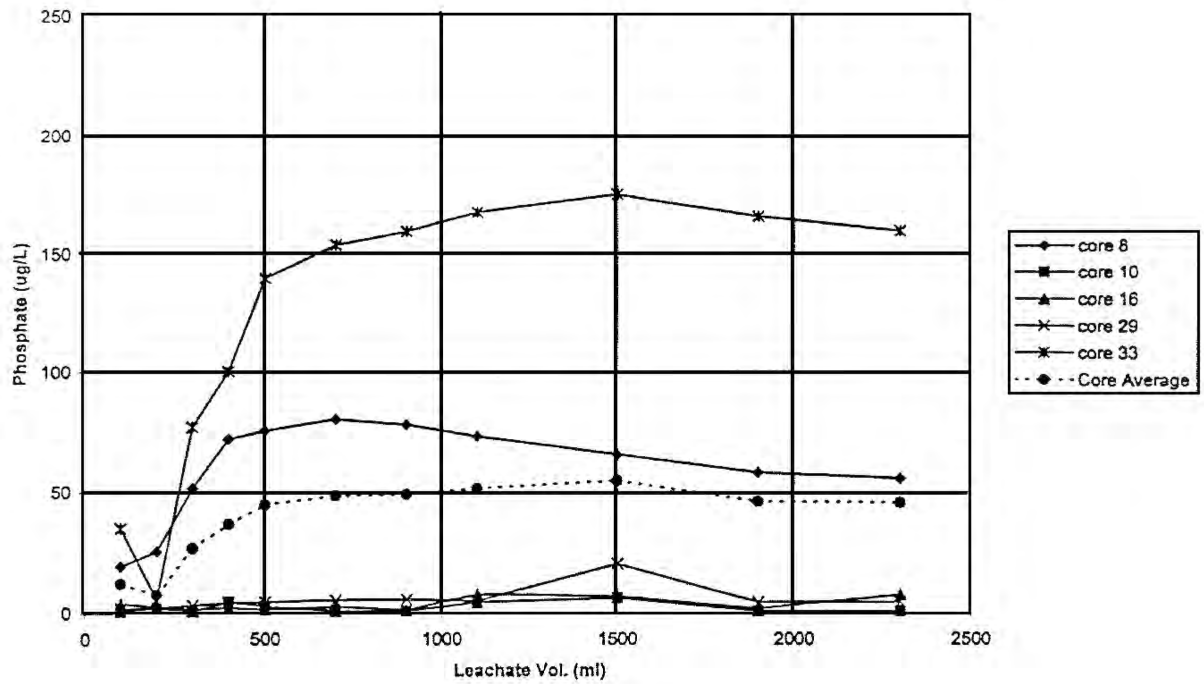


Figure 4-10—Phosphorus release during leaching of undisturbed soil cores from upland forested sites (UPFOR) (from Harlow 1998).

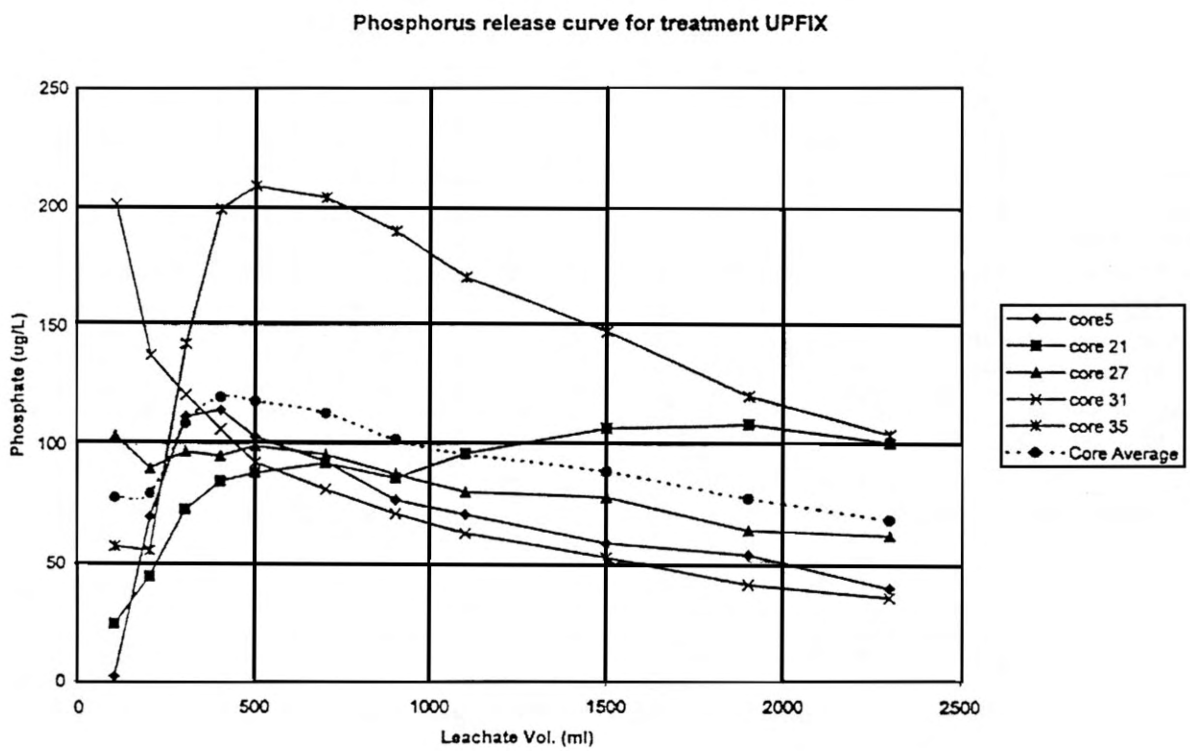


Figure 4-11—Phosphorus release during leaching of undisturbed soil cores from upland sites with nitrogen fixing vegetation (UPFIX) (from Harlow 1998).

Comparison to Background Concentrations and Water Quality Standards

Table 4-3 provides the average annual flow-weighted total-P concentrations for the nine LTIMP streams. Accompanying these concentrations are the numeric water quality standards and objectives established by California and Nevada. For California, each creek is identical with a desired concentration of 15 µg/L. This concentration was exceeded in each of the ten years from WY 1987 to WY 1996. For most of the LTIMP creeks, it was exceeded by a factor of two to four times; however, in Ward and Blackwood Creeks during WY 1995 and WY 1996, the 15 µg/L was exceeded by four- to eight-fold. Only General Creek approximated the water quality objective with average annual TP in the range of 17 to 31 µg/L. This observation supports the use of General Creek as an indicator of "control" conditions. The California objectives are particularly stringent, they are aimed at restoring historical or better water quality. The Nevada value of 50 µg/L is based on data collected during the more recent period WY 1988 to WY 1995 and consequently reflects more current rather than historical conditions. Even so, Incline Creek always exceeded this value, while Glenbrook Creek does so about half the time. With a range of 21 to 42 µg/L, TP in Logan House Creek was relatively low, again reflecting its undeveloped nature.

In their analysis of land use and water quality in streams tributary to Lake Tahoe, Byron and Goldman (1989) used the y-intercept from plots of disturbed, low, and high hazard land versus TP as representative of control conditions, i.e., those with little or no human disturbance. At the time of their analysis adequate data was only available for streams on the north, west, and south sides of the lake; monitoring of the eastside creeks was not yet fully underway. They found that the predicted TP concentration without disturbance was in the neighborhood of 12 to 15 µg/L, which supports the California water quality objective of 15 µg/L (representing historical conditions).

Table 4-3—Mean annual total phosphorus (P) concentrations (µg/L) in each of the monitored streams in the Tahoe basin. Values were obtained by dividing total P load by annual discharge. Each year 30-50 samples are taken for chemical analysis from each stream as part of the Lake Tahoe Interagency Monitoring Program (LTIMP). A Water Year (WY) extends from October 1 to September 30. LTIMP streams include TC = Trout Creek, UT = Upper Truckee River, GC = General Creek, BC = Blackwood Creek, WC = Ward Creek, TH = Third Creek, IN = Incline Creek, GB = Glenbrook Creek and LH = Logan House Creek. Combined these account for approximately 50% of the annual inflow to Lake Tahoe, ND denotes that data is not available.

Station/WY	87	88	89	90	91	92	93	94	95	96	Nevada[1]	California[2]
TC	ND	ND	42	42	32	34	44	36	58	49		15
UT	48	40	43	32	37	23	40	28	53	44		15
GC	24	23	18	21	21	17	23	17	28	31		15
BC	43	33	35	34	51	31	57	27	71	126		15
WC	33	31	33	34	35	33	55	39	67	101		15
TH	ND	11	160	75	241	119	164	100	345	60	50	
IN	ND	ND	98	81	74	68	81	76	131	67	50	
GB	ND	ND	70	42	48	33	ND	60	78	74	50	
LH	ND	ND	32	34	26	21	28	20	42	30	50	

Notes:
[1]Nevada Requirements to Maintain Existing Higher Quality (RMHQs) are based on the 95th percentile using the WY 1988-1995 data set.
[2]California numerical objectives based on 90th percentile values for historical (often pre-1975) water quality.

Directly differentiating between the natural and the human impact contribution to P delivery is difficult because there is no adequate database for predevelopment water quality conditions in the LTIMP watersheds. However, as noted above, the General Creek watershed can be considered as relatively undeveloped because it is in a state park. If one characterizes P transport in General Creek and applies these relationships to a more developed watershed nearby, one can get a glimpse as to what P transport would be like if that nearby watershed were not subject to human disturbance. This technique enables a preliminary differentiation between natural and human-influenced P delivery. Of the monitored watersheds adjacent to General Creek, Ward Creek is the best candidate for comparison. Housing subdivisions and roads are the major human influences in Ward Valley. General and Ward Creeks have approximately the same precipitation amounts, vegetation types, and basin area; however, they are not identical with respect to all aspects of geomorphology. For example, the General Creek watershed consists primarily of a granitic geology, whereas the Ward Creek watershed contains significant portions of volcanic material. In addition, channel morphologies in the lower reaches of the main stems are different (Norman 1999).

In his analysis of this situation, Hatch et al. (1997) presented a simplistic "model" of TP loading in which annual areal TP load is significantly related to annual discharge for General Creek. This model is intended only for problem-solving purposes. Assuming that current hydraulic discharge in Ward Creek would be characteristic of undeveloped conditions, the discharge for Ward Creek was substituted into the equation generated from the General Creek model. The results of this extrapolation indicated that Ward Creek areal TP loading would be much lower during high precipitation and discharge years (Figure 4-12) if the watershed had no development. 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 percent in WY 1983, by 39 percent in WY 1984, by 74 percent in WY 1986, by 33 percent in WY 1993, by 58 percent in WY 1995, and by 144 percent in WY 1996. That actual measured loading from Ward Creek was similar to predicted loading based on the General Creek model during low precipitation/low flow years but was greater during high precipitation/high flow years supports the observation mode by Hatch (1997) that TP loads did not increase greatly with precipitation levels until a certain threshold level of precipitation was reached.

Nitrate Transport

Coats and Goldman (1993) published a study on nitrate transport in subalpine streams in the Tahoe basin. LTIMP data from Ward Creek, Blackwood Creek, General Creek, the Upper Truckee River, Third Creek, and Snow Creek were used to develop a linear model relating nitrate-N concentration to two discharge variables. The data set comprised >3,100 mean daily discharge and nitrate concentration values representing 45 watershed years. The goal was to compare the relative contribution to nitrate concentration of two dominant water types: short flow-path water, which occurs during storms and snowmelt, and long flow-path water, or base flow.

The first variable was a reciprocal function of discharge, derived from a mixing model for both water types in an open system. The second variable used either cumulative water discharge or cumulative nitrate load for the water year. Stepwise linear regression was used to fit model parameters to the data. Both independent variables made a highly significant contribution to explaining the concentration variance. Values of R^2 ranged from 0.22 to 0.45. For one catchment, the model was fitted to data for eight separate water years; it explained up to 80 percent of the variance in nitrate concentration. The results of this study indicated the Coats and Goldman model can be used to distinguish anthropogenic nitrate sources from the ion pulse associated with early snowmelt and can be developed into predictive models for estimating total N load.

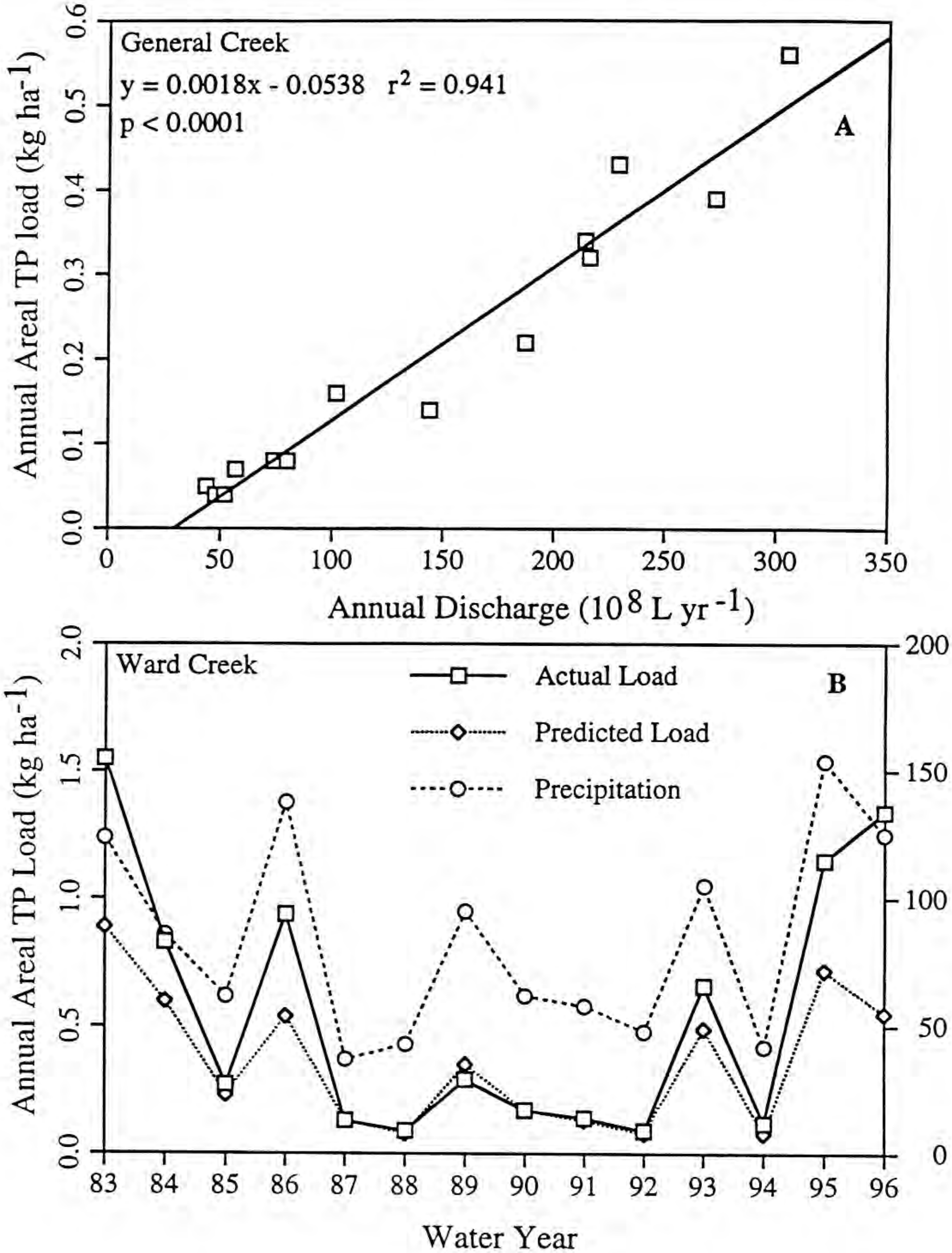


Figure 4-12—Discharge versus areal TP load relationship for General Creek used to predict areal load from Ward Creek under similar land use conditions. This undisturbed value is compared to actual measured loading from Ward Creek under current conditions of development in the watershed (from Hatch 1997).

Current Projects

Two projects of significance are in the planning or pilot study stages. The first is an integrated and comprehensive focus on nitrogen, phosphorus, and suspended sediment contribution from urban runoff and runoff from intervening zones. As suggested in the nutrient budget at the beginning of this chapter, these may be very important sources of phosphorus to Lake Tahoe and are areas where restoration/abatement may be successful. A more detailed understanding of nonpoint source loading within these regions is critical. Based on discussions at the 1998-1999 Tahoe Science Symposia, deliberations of the Tahoe Water Quality Working Group, and planning with basin agencies, efforts are now underway to coordinate the monitoring and research in this area.

The second project that commenced in the Spring of 1999 is an evaluation of the historical LTIMP stream discharge and water quality database. Among other things, this study evaluated the long-term data for trends in changing water quality conditions; identified the influence of climate, precipitation, and runoff on stream water quality; further evaluated sources of nutrient and sediment within LTIMP watersheds in a more statistically robust manner than previously used, and examined the differences among watersheds to determine the influence(s) of natural geomorphic characteristics and human land use patterns on stream loads and concentrations.

In summary, understanding phosphorus dynamics within the Tahoe basin will require much more in the way of research effort. For example, the long-term changes in phosphorous loading are unknown. Actual transport mechanisms, including colloid transport, also need further investigation, given the apparent association between P loading and the loss of lake clarity.

What is the evidence linking tributary sediment and nutrient loading to land use and watershed geomorphologic characteristics?

Numerous previous studies in the Tahoe basin suggest that, on a localized scale, land use can have a large effect on the water quality of surface runoff. Examples include Glancy (1969, 1982), Dugan and McGauhey (1974), Goldman (1974), Kroll (1976), Leonard et al. (1979), California Department of Conservation (1969), Perkins et al. (1975), Coats et al. (1976), California Tahoe Conservancy (1987), Garcia (1988), Loeb (1990), Woyshner and Hecht (1990), Reuter et al. (1990), Reuter and Goldman (1992), Lowry et al. (1994). No attempt is made here to summarize all the data available on this topic.

Because the basin does not contain many activities with point source discharges, watershed management of nonpoint source pollution has been adopted as the necessary approach for protecting lake water quality and clarity. Currently, more than 30 state, federal, and local agencies and legislative groups are active in the basin. Based on the principle that environmental disturbance accelerates the delivery of nutrients and sediments to Lake Tahoe, such management actions as the following have been initiated:

- Lake Tahoe Basin 208 Plan;
- TRPA Compact;
- Formation of the USDA Forest Service's LTBMU;
- Creation of the California Tahoe Conservancy for the purpose of administering erosion control and land restoration projects;
- Passage of the Santini-Burton Act by Congress;
- Formation of LTIMP;
- Adoption of environmental thresholds by TRPA;
- Establishment of Water Quality Working Group;
- Numerous Erosion Control Technical Advisory Committees;
- The Lake Tahoe Federal Legislative Agenda;
- The IPES Program;
- The Presidential Forum Deliverables;
- The Tahoe Bonds Acts in Nevada; and
- The Environmental Implementation Plan (EIP).

Below, three of the most comprehensive analyses of land use and stream water quality are summarized. Most of these use LTIMP data as the basis for their evaluation.

Multiple Watershed Comparisons

Early Studies—The Upper Truckee, Incline Creek, and Ward Creek watersheds were studied in 1970 to evaluate the potential effects of residential and commercial development on tributary water quality (Lake Tahoe Area Council and United States Federal Water Quality Administration 1970). Although no baseline data were available, the study provided a "real time" comparison between the discharge water quality from a well-developed watershed (Upper Truckee), an actively developing watershed (Incline), and a relatively undeveloped watershed (Ward). Incline Creek water quality was consistently more turbid and contained a higher nutrient concentration than either of the other watershed tributaries, followed by the Upper Truckee and then Ward Creek, the undeveloped watershed. Because the streams did not have equal discharge flow volumes, the data cannot be quantitatively compared. However, the Ward Creek nutrient variation was seasonal, while the other two watersheds exhibited concentration peaks at times when human activity was greatest.

Sediment Yield—Hill and Nolan (1990) presented the results of a study intended to assess those factors that might affect variations in average annual suspended sediment yields of streams tributary to Lake Tahoe. The relative importance of natural and land use-related factors were considered using regression analysis to examine empirical relationships between selected independent variables and suspended sediment yields.

To include a wide range of flow conditions, Hill and Nolan used LTIMP data collected between 1981 and 1985. which included the Upper Truckee River and General, Blackwood, Ward, Snow, Third, and Trout Creeks. This period included two very wet years, which was important because sediment yields are greatly affected by high flow conditions. The authors point out that although none of the streams were on the east side of the lake, where geologic and climatic conditions are different, this analysis included approximately 80 percent of the Lake Tahoe basin.

Drainage density (total length of stream channels in a watershed divided by total watershed area) and road miles were selected to represent channel erosion and land use, respectively; however, because a wide variety of drainage-basin characteristics can affect sediment yield, Hill and Nolan considered additional independent variables. These variables included channel gradient, ground slope, main channel length, basin area, relief, relief ratio, elongation ratio, hypsometric analysis index, percent of watershed in high, moderate, and low erosion hazard rating, road miles, road density, drainage density, geologic composition, and average precipitation.

Drainage density was by far the most important variable in explaining variations in sediment yield during the period of record; i.e., an r^2 value of 0.77. The importance of drainage density as possibly controlling sediment yield for the entire basin is less clear because sediment yields are low but drainage densities are high on the eastside of the lake. Other independent variables that explained variation in sediment yield included percentage of basin area underlain by metamorphic rocks (r^2=0.42), average annual precipitation (r^2=0.41), and average ground slope (r^2=0.40).

Individually, road miles and road density (road miles per unit watershed area) accounted for little of the observed variability in suspended sediment yields. However, they did help improve the explanation of variability when used in concert with drainage density and precipitation in multiple regression analysis. Drainage density and road miles together explained 83 percent of the variation in sediment yield, while drainage density, road miles, and precipitation accounted for 89 percent of the variation over the period of record. Hill and Nolan point out that while previous studies have indicated that land use disturbances can increase sediment yield within individual watersheds by an order of magnitude (Glancy 1982), the large differences between physiographic features appear to account for most of the observed variability of suspended sediment yields.

The correlation between percent land use and average discharge sediment concentration in Tahoe basin tributaries also is the subject of current research of Comanor et al. (unpublished). Land use information was derived for seven Tahoe basin tributaries using the TEGIS database. Four buffer zones were defined adjacent to each stream encompassing distances of 50 m, 100 m, 250 m, and 500 m, with a fifth scenario that considered the total watershed as a whole. Discriminant analysis was used to verify the study approach. Within ARC/VIEW, percent cover was calculated for five land use types (residential, commercial, natural, recreational, and miscellaneous) for each of the buffer zones and for the entire watershed. Only natural surfaces exhibited a negative correlation with sediment discharge. All other defined land uses exhibited a positive correlation. Natural land use demonstrated a maximum negative correlation within the 100 m buffer zone. In other words, the greater the amount of natural undisturbed conditions within 100 m of the stream, the lower the average amount of sediment discharge. Maximum correlation (r^2=0.79) for recreational use was within the 50-meter buffer zone, indicating that the greatest adverse impact from recreation activity would occur within 50 meters of the stream. For commercial land use, the correlation increased with increasing size of the buffer zone. This suggests that the impact is more related to the degree of commercial land use than it is to location relative to a given tributary. Correspondence analysis indicated that the overall pattern of land use among the seven tributaries did not significantly differ. Multiple regression models of percent land use and average sediment discharge concentration for each of the buffer zones (r^2=0.81) also indicated a significant cumulative effect from all land use types. Interpretive assessment thus far clearly illustrates that zoning for land use planning must consider both existing and proposed land use types, as well as the respective distance from the stream. However, because of the probable role that the road network plays in conveying runoff, streamside buffer strips are most likely to have an impact on a local scale and not at the watershed level.

Nutrient and Sediment Concentration—Byron and Goldman (1989) evaluated the relationships between land use and water quality in 10 Tahoe basin watersheds. The water quality parameters used in this study were TSS, TP, and nitrate. The land use characteristics considered were the disturbance level and coverage by impervious surface of various land use categories.

This analysis combined data sets from LTIMP and USDA Forest Service stream water chemistry and TRPA land use data. The LTIMP streams included the Upper Truckee River, Trout Creek, General Creek, Ward Creek, Snow Creek, and Third Creek (75 to 100 samples each, per year). The USDA Forest Service streams were Saxon Creek, Meeks Creek, Big Meadow Creek, and Grass Lake Creek (15 samples each, per year). As with the Hill and Nolan evaluation, adequate data from eastside streams were not yet available. The nutrient concentrations used in this analysis were the flow-weighted averages of four annual values for WY 1981 to 1984. Byron and Goldman (1989) noted that these flow-weighted concentration values encompassed normal, drought, and high-water years and thus provided a representative flow regime. In addition, they noted that because nutrients and sediments may be variably stored within watersheds during dry years and flushed out during wet years, this multi-year average is a better method for comparing watersheds than an analysis based on data from a single year.

They developed two land use classifications for each watershed. The first was termed disturbed or covered low hazard land (DCLH), which represents that portion of each watershed assigned to disturbed or covered land (impervious) capability classes 4 through 7, as defined by the Bailey (1974) system. Classes 4 through 7 have a gradient ranging from 0 to 30 percent and are rated as slight to moderate erosion and runoff potentials. They are lands that are relatively less sensitive and may be allowed future development. These classes were considered least likely to yield high amounts of sediment and nutrients through the disturbance associated with construction activities. The second classification, disturbed or covered high hazard land (DCHH) represents that portion of the watershed assigned to disturbed or impervious covered land capability classes 1 through 3. These classes have gradients of nine to >50 percent, are rated as having relatively high or moderate erosion potentials, and are restricted from future development. In the Byron and Goldman analysis, DCHH included stream environment zones. That portion of DCHH characterizes watersheds on the basis of their relative disturbance to their most erodable areas. Land use mapping was considered fine enough to allow the authors to differentiate watersheds with a range of only six percent in total disturbance and coverage. Nutrient and sediment concentration values were linearly regressed against both DCHH and DCLH to evaluate the potential effect of land disturbance on runoff water quality.

It was determined that under conditions of little or no human disturbance in which DCLH and DCHH were equal to zero (i.e., representative of control conditions), the concentrations of soluble reactive-P and nitrate-N would be predicated at 5 to 7 μg/L each, 12 to 15 μg/L for total-P, and 10 to 15 mg/L for TSS. Under conditions of increasing human disturbance (DCLH or DCHH$\geq$0), the magnitude of cumulative disturbance within a watershed was usually significantly related to runoff water quality. Nitrate-N and TSS showed significant regression coefficients to DCHH but not to DCLH. TP showed significant relationships with both, but the slope of the DCHH equation was 50 percent greater, suggesting a higher level of sensitivity to P transport from the high hazard lands. Similar patterns were seen for nitrate-N (DCHH 125 percent greater slope) and especially TSS (DCHH 250 percent greater slope). The mere presence of high hazard lands within a watershed did not appear to have a significant effect on nutrient or sediment yield. Byron and Goldman observed that when the 10 watersheds were compared on the basis of the total area made up of high hazard lands (i.e., regardless of the proportion of human disturbance or coverage), there were no statistically significant relationships to the water quality parameters.

This study indicates that the long-term average nutrient flux originating from nonpoint sources closely reflects the intensity and location of disturbance in the watershed. As time proceeds and as watersheds move toward a state of equilibrium among natural processes, recovery, and disturbance, the exact nature of these relationships may change.

Goldman (1989) has reported water quality to be more sensitive to land use than to geomorphology or soil type. He found higher nutrient loading of both nitrogen (N) and phosphorus (P) in areas where there has been documented land disturbance, whether natural or anthropogenic. Soil disturbance reduces both vegetative cover and soil stability. Reduced vegetation causes reduced nutrient uptake and diminished soil stability, which increases erosion, sediment transport, and the discharge of sediment-associated P. For example, although Blackwood Creek contains little residential development, it exhibits relatively high levels of phosphorous loading. In addition to a significant fire history, the creek was mined for gravel beginning in 1960. As a result, sediment and debris have washed into the lake, forming a large spit at the creek mouth. The creek is still suffering from continued erosion (Goldman 1989; Tahoe Regional Planning Agency 1996).

Phosphorus Concentration and Load

Multiple Watershed Analysis—Most recently, the task of relating watershed parameters 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 (Hatch 1997). The discussion below comes directly from Hatch's recent doctoral dissertation. Most watershed parameters are fixed geologic or morphologic features. Even the road and development categories can be assumed to be constant because there were no new roads built during the WY 1989 to 1996 period and because development coverage has been strictly regulated since 1987. After linear univariate regressions were performed, parameter associations with $p < 0.05$ were considered for additional analysis. Watershed characteristics included drainage area, precipitation, main channel length, main channel gradient, drainage density ground slope, aspect elongation ratio, relief ratio percent high, moderate, and low hazard land, geologic composition, total road mileage, road density, road coverage and development coverage. Many of these features were taken from Hill and Nolan (1990).

While some important watershed variables influencing discharge, P loads, and P concentrations may have been overlooked, it is interesting to note that many of the listed watershed parameters did not correlate well with P-related variables in LTIMP streams (Hatch 1997). These results were somewhat surprising because the literature indicates that watershed geology can strongly influence 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 also has been noted by Dillon et al. (1991) and Svendsen et al. (1995). The LTIMP data for inter-watershed discharge were associated positively with basin area and main channel length but were negatively associated with channel gradient and basin relief ratio. Positive associations also existed among discharge and road length, road coverage, and development coverage. Inter-watershed PO_4^{-3} 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 (liters/ha) had similar associations as seen for discharge but also was linked to precipitation. Areal loads (kg/ha), however, lost many of the associations seen for loads (kg), suggesting that basin area exerts a strong influence on PO_4^{-3} and TP loads in LTIMP streams. Inter-watershed TSS and TP concentrations (and by association PP concentrations) were associated with percent surficial deposits, which are located primarily adjacent to stream channels. Inter-watershed PO_4^{-3} concentrations were correlated with drainage density and road density.

Hatch (1997) suggested that the general lack of significant correlations 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 truly variable, changing significantly from year to year. Using mean (or even modal) values may mask the true variability of the hydrologic system, especially when one compares water quality to nonvariable watershed parameters. Also, as suggested by Hill and Nolan (1990), the relationships under investigation may not be linear. Second, it may be the case that despite their seemingly broad range of characteristics, 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. 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, but may appear quite similar when compared to a data set from a more regional, national, or global scale. Finally, as indicated earlier, it may be the case that streambank erosion is the primary variable driving sediment and P transport in the LTIMP streams. If indeed a significant portion of the TSS and supposedly phosphorus is derived from streambanks, direct contribution of these materials to the streams via surface and subsurface flow may not be as important as the contribution of runoff water, which would have a direct impact on streambank processes. Quantification of sediment movement from this source would rank the significance of the contribution of streambanks to the overall transport of stream sediment and P to Lake Tahoe.

The process of snowmelt water reaching Tahoe streams by either ground water or overland flow has been altered by human activities. The amount of artificial impermeable surface coverage was significantly correlated with discharge, TP load, and PO_4^{-3} load, but this does not necessarily mean causation. In addition to discharge and loads, basin area was also a strong predictor (positive relationship) of main channel length ($r^2 = 0.884$, $p < 0.001$), road length ($r^2 = 0.843$, $p < 0.001$), road coverage ($r^2 = 0.965$, $p < 0.001$), and development coverage ($r^2 = 0.766$, $p = 0.002$). Thus the relationship of impermeable surface with discharge and loads only might be a statistical one, with all these variables (discharge, loads, channel length, road length, road coverage, and development coverage) related directly to basin area and not each other. Again, correlational analysis may not be the most appropriate method of statistical analysis for this type of data. However, there are sound reasons why road and development coverage can affect stream discharge and loads.

First, as urbanization increases, so does the amount of impervious coverage (Beaulac and Reckhow 1982). Road coverage can influence stream discharge by not allowing surface water to infiltrate the ground water. The runoff water either flows onto bare ground next to the impermeable coverage where it can erode soils, or the water is channeled into storm drains that eventually lead to streams or the lake. Stormwater runoff not only carries debris and nutrients, but it also causes heightened storm hydrograph pulses. 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 those in which natural stream systems have evolved (Beaulac and Reckhow 1982), increasing the potential for erosion higher up on streambanks.

Roads also can influence nutrient movement indirectly via exposure of roadcuts. The steep terrain and extensive subdivision developments in the Tahoe basin result in large areas of roadcuts; these bare surfaces can be eroded, and the liberated sediment and nutrients can be transported to nearby streams. However, Glancy (1977) argued that roadcuts in the Glenbrook watershed were not significant to the overall TSS load. Because the probability of sediment reaching a stream is in part proportional to distance from the stream, only roadcut sediment draining to stream areas will influence stream TSS loads.

Unpaved logging roads can be a significant source of nutrient export. Megahan (1987) asserts that such roads have on-site impacts, such as reduced forest productivity and increased runoff and erosion, and off-site impacts, such as altered streamflow, water quality, and channel morphology. Montgomery (1994) argues that logging roads increase the effective length of the channel networks, implying that roads can act as routes of sediment transport, not unlike streams. While these risks occur in association with the salvage logging that currently occurs with the Tahoe basin, commercial logging of the type cited in Montgomery's study has not occurred within the basin for over 30 years. Current salvage operations proceed under very strict rules that are likely to limit erosion (Unsicker 1999).

Managers also need to be aware of the distinction between historic logging roads, such as remnants from the Comstock logging period of the late 1800s, and current logging operations. Many of the historic logging roads now appear as drainage channels or swales. Over the last 100 years, channel morphology has been modified, and in many cases vegetation has been established (Lindström, Chapter 2 of this document). No comprehensive reports on these old logging-roads, as sources of sediment or nutrients have yet been uncovered.

Overland flows have not been observed frequently in the Sierra Nevada (Skau et al. 1980). Rarity of overland flow in forested catchments also has been demonstrated in New Hampshire (Meyer and Likens 1979), in other areas of the eastern United States (Beaulac and Reckhow 1982), and in Japan (Chikita 1996). Coarse sandy soils and thick layers of forest duff (partially decayed organic matter) in the Tahoe basin most likely allow water to easily percolate into the soil. Much precipitation probably reaches Tahoe streams via ground water (subsurface quickflow), implying that in forested catchments the major sediment/nutrient sources to streams come from channel 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 basin 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 course particulates (Fenn and Gomez 1989), which can be deposited and re-deposited several times along the course of a stream (Walling 1983). Heavy armoring and stair-stepping in mountain streambeds dissipates much of the energy caused by steep stream slopes, greatly limiting the amount 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 streambed erosion (Svendsen et al. 1995).

The Influence of Subwatershed Characteristics on Phosphorus Loading—Areal P loading is a direct measurement of how watershed processes influence P movement to streams. The subwatersheds on the same Tahoe stream behave similarly with respect to areal P loading during low precipitation, and hence low discharge, years. However, the subwatersheds displayed differing behavior during relatively high precipitation years. What is causing the observed changes in areal P loading as one moves downstream in LTIMP watersheds during high precipitation years? Water Year 1995 offers an excellent opportunity to examine this question. Hatch (1997) addressed this question using the LTIMP database for Incline Creek, Trout Creek, the Upper Truckee River, and Ward Creek. Three stations are monitored on each stream as part of the LTIMP monitoring. Location descriptions are the same as those presented above in the discussion of nutrient loading from Lake Tahoe tributaries.

Using data for PO_4^{-3}, DOP, and PP collected in WY 1995, Hatch reported that although the INC2 (middle to lower portion of the more extensive east fork of Incline Creek) subwatershed produced greater areal P loads than the other Incline Creek subwatersheds, none of the land use parameters considered appeared to explain intra-watershed differences. The INC2 subwatershed had the lowest gradient and shortest channel lengths for Incline Creek, which might imply that the physical energy to move sediments and nutrients and the stream channel P sources would be low. However, the INC2 subwatershed contains portions of a golf course, a ski resort/parking lot, and residential development, which may be contributing large amounts of P to the stream between stations INC3 and INC2. Although the other lower elevation, subwatershed (INC1) also contains residential development and part of a golf course, its areal P loading rates were less than those for INC2. Hence the ski resort/parking lot areas in the INC2 subwatershed may contribute to the enhanced areal P loading rates observed there in WY 1995.

Areal DOP and PO_4^{-3} loading rates of all three Trout Creek subwatersheds were very similar in WY 1995, suggesting that similar processes are taking place with respect to dissolved P transport from the subwatersheds. Watershed parameters are similar for the three areas, except for decreasing slopes and increasing road lengths/densities in the downstream direction for Trout Creek stations. The relatively low areal PP loading for TRT1 during WY 1995 may be a result of a relatively low stream and subbasin slope but may also be due to the presence of a wetland area along a tributary stream in this downstream portion of the watershed. Cold Creek enters the main stem of Trout Creek between stations TRT2 and TRT1. The Cold Creek watershed is completely contained in the TRT1 subwatershed and supplies over 50 percent of the discharge. However, just prior to its confluence with Trout Creek, Cold Creek passes through a large (10.5 ha) newly restored wetland (former Lake Christopher). Although Cold Creek is confined to its main channel during low discharge periods, during the high discharges of spring snowmelt the creek spreads out over the wetland. This behavior most likely removes large amounts of sediment and PP, hence could result in a lower areal PP loading in the Cold Creek subwatershed than would be expected without the presence of the wetland. The overall effect may be to cause Cold Creek to contribute relatively PP-dilute water into Trout Creek, and thus the TRT1 subwatershed had a lower areal PP loading rate than either the TRT2 or TRT3 subwatersheds during WY 1995.

DOP and PO_4^{-3} areal loads were quite similar for the three Upper Truckee River subwatersheds, indicating the presence of similar dissolved P loading mechanisms. The UTR1 subwatershed, however, exhibited relatively high areal PP loading rates. This subwatershed is characterized by relatively low slopes, high percentages of surficial deposits, low percentages of glaciated granite, and high road densities in comparison to the UTR3 and UTR5 subwatersheds. Surficial deposits, located primarily along stream channels, may be contributing PP to the Upper

Truckee River through unstable streambank erosion (Hatch 1997).

The lower subwatershed (WRD8) had much higher areal PP and PO_4^{-3} loading rates than either of the upstream areas. High percentages of surficial deposits and very high road densities may combine to create enhanced loading conditions in this area. An explanation for the net loss of DOP between Ward Creek stations WRD7A and WRD8 may lie in how human activities have altered the watershed. Because there are no tributary inputs between stations WRD7A and WRD8, most discharge and dissolved P must be entering the stream via ground water or overland flow. Beaulac and Reckhow (1982) argue that urbanization increases will result in increased impervious surface area, which in turn will create increased annual surface runoff and decreased ground water recharge. If ground water recharge is being reduced in the WRD8 subwatershed due to high housing densities, subsurface processing of soil and rhizosphere DOP sources (Leonard et al. 1979) also may be reduced. The net result may be a large reduction of ground water DOP inputs to the stream between stations WRD7A and WRD8. This outcome, along with the potential of stream bottom sediments and vegetation to absorb DOP (Meyer 1979), may partially explain the net loss of DOP in the lower reaches of Ward Creek. Details of phosphorus chemistry in the Lake Tahoe tributaries are not well known at this time. The extent of such transformations as those between inorganic-P and organic-P and between particulate-P and dissolved-P require study before unambiguous conclusions can be made.

According to Hatch (1997), an important point to note is that certain areal P loads from the upper subwatersheds in Incline Creek (INC3: DOP and PO_4^{-3}), Trout Creek (TRT3: all P forms), and the Upper Truckee River (UTR5: DOP and PO_4^{-3}) were equal to or greater than their respective downstream subwatersheds (INC1, TRT1, and UTR1). Because the upper watersheds for these streams are considered undisturbed due to their relatively low levels of human activity, their higher P loading rates suggest that such natural factors as slope are a dominant influence. Much smaller slopes may lead to relatively lower loading rates in the lower watersheds, but greater levels of human development in the lower watersheds may lead to higher loading rates than would be expected under undisturbed conditions.

The overall results of this study indicate that although P concentrations may increase, decrease, or remain constant in the downstream direction, P loads will always increase in the downstream direction. Reduction of areal TP loads should focus on the lower subwatersheds where sources and loading are the greatest. Future research should address the question of how dissolved P (both PO_4^{-3} and DOP) is absorbed/adsorbed/desorbed and transformed (e.g., into PP) along the course of a single stream. Knowledge of the interaction rates between stream sediment P and stream water P will give an idea of whether Tahoe streams can continue to buffer human-enhanced P fluxes into the future.

Effects of Site Condition on Soil Permeability and Sediment Yield

Erosion potential is linked with amount and type of runoff, as well as disturbance. Guerrant et al. (1990, 1991) evaluated the runoff and site-specific erosion potential of the Cagwin soil (common to the Tahoe basin). This work was intended to examine soil's ability to be infiltrated under conditions of excessive artificial precipitation. Study sites consisted of undisturbed forest soils with natural duff (P1), undisturbed without natural duff (P2), disturbed without natural duff (P3), and disturbed with natural duff removed (P4). Artificial rainfall was applied to measure runoff and infiltration parameters on each site.

The P2 site demonstrated a very high apparent infiltration capacity (due to the very high storage capacity of the duff layer), and what little runoff there was contained little sediment. The P2 condition had the highest percent runoff and P4 had the lowest, at final infiltration. The P4 condition had the lowest runoff but also had the highest sediment loads. The disturbance and removal of duff enhanced the infiltration capacity but also the potential for sediment transport. Disturbance and particle detachment at the soil surface caused individual mineral particles to be more easily transported by a small amount of runoff. This was especially apparent on the steeper slopes (Table 4-4), however, the interrill erosivity (that is, the erosion that occurred among very small brooks) was found to decrease with time for all sites. Slope gradient had a positive effect on the amount of interrill erosion. Although this study demonstrated which site conditions (disturbed/undisturbed, duff/no duff) were more likely to erode, application to other Tahoe basin soil types of different erosivity classification cannot be directly inferred.

Guerrant et al. (1991) also noted that only interrill erosion was examined and not rill erosion, which may be a greater source of sediment discharge on some soils. A subsequent University of Nevada, Reno (UNR) study focused on sediment discharge from four different plot conditions on Meeks Creek (Naslas 1991). The conclusions were similar to those of Guerrant et al. (1991) in that soil disturbance and slope were identified as the greatest predictors of sediment transport. The highest sediment came from the wooded disturbed site without duff, and the least from the wooded natural site with duff intact. The open natural and open disturbed sites produced erratic sediment discharge, while the wooded disturbed site demonstrated decreasing erosivity with time. The sites with duff showed an increase in infiltration with time as the water repellency decreased.

Sullivan et al. (1996, 1998) conducted a study to quantify and delineate spatial variations in surface infiltration and to estimate infiltration parameters used in computer models for simulating runoff quantity following summer rainstorms from a small watershed (Incline Creek) in the Tahoe basin. Field tests that give the infiltration parameters of sorptivity and hydraulic conductivity, two parameters found in the Philip infiltration model, were performed in the watershed with the use of a disk permeameter. These field data were combined with coverages in an existing GIS database and field observations of surface attributes (soil type and vegetation), that are known to contribute to variation in infiltration rates. Statistical tests performed on

Table 4-4—Cumulative runoff (CR) and cumulative interrill erosion (CIE) from experimental plots after 1 h of simulated rainfall[1].

	Plot Condition					
	P2		P3		P4	
Slope	**CR**	**CIE**	**CR**	**CIE**	**CR**	**CIE**
%	L	g m^{-2}	L	g m^{-2}	L	g m^{-2}
0-15	18.8	79.4	12.8	171.3	11.3	136.3
15-30	11.2	301.3	15.7	244.5	14.6	37.6
>30	15.2	634.2	13.5	285.9	13.5	1,083.8

	Significance Matrix											
	Slope						Plot Condition					
	P2		P3		P4		P2		P3		P4	
	CR	**CIE**	**CR**	**CIE**	**CR**	**CIE**	**CR**	**CIE**	**CR**	**CIE**	**CR**	**CIE**
0-15	a[2]	a	a	a	a	a	a'	c'	b'	a'	b'	b'
15-30	a	b	a	b	a	b	a'	a'	b'	b'	b'	c'
>30	a	c	a	c	a	c	a'	b'	b'	c'	b'	a'

Notes:
[1]Values calculated from model estimation of field data.
[2]Significance of slope on cumulative runoff and cumulative interrill erosion is compared by column only and letters a, b, and c. Significance of plot condition on cumulative runoff and cumulative interrill erosion is compared by row only and letters a', b', and c'. CR and CIE followed by the same letter are not significantly different at $P = 0.01$.

field test data indicate that the only surface attribute that influences variations in infiltration rates in this watershed (owing mainly to limited variations in soil type) is vegetation. Further, time-to-ponding calculations, which indicate when and if runoff might occur following the start of a precipitation event, indicate that for most precipitation events likely to occur in this area during the summer, infiltration in all but nonforested areas is unlikely.

Tahoe basin roads act as pathways for sediment transport. If left unpaved, roads and trails also are a source of sediment. Studies on Trout Creek and the Upper Truckee River (California Department of Conservation 1969) have reported that roadways were responsible for 48 percent of the suspended sediment found in Tahoe basin stream flows. Unpaved logging roads transport fine particles mobilized by logging operations. Even when logging is not currently active, the roads still exist as a source of sediment and nutrients and for easy transport to the streams.

Nutrient loading also is affected by hydrologic discharge. For undeveloped watersheds, early snowmelt discharges the largest pulse in stream water N. During freeze-thaw cycles, the nitrogen becomes concentrated, resulting in an initial flush when the snow melts. Indeed, Coats and Goldman (1993) reported that the first 50 percent of surface runoff accounted for approximately 75 percent of the nitrate-N load during the 1980 water year.

An undisturbed subwatershed of Clear Creek near the Tahoe basin was studied in 1982 and 1983 (Rhodes 1985). The forested area had no development, had never been logged, and therefore was considered representative of a natural state. The soils (primarily acidic Cagwin series) were very permeable. Winter precipitation generally infiltrated through the vadose zone (i.e., above the ground water), to the ground water, and then to the discharge tributary. Any nitrate entering the stream would have come from direct meltwater. The site was found to be extremely effective at removing nitrate. Although during the summer and fall, vadose zone nitrate concentrations were elevated, ground water sampling showed nitrate concentrations an order of magnitude below that contained in natural precipitation. Denitrification was suggested as the primary nitrate removal mechanism. The findings of this study are believed to have characterized N behavior in tributary discharge from pristine watersheds on eastern slopes of the Sierra Nevada.

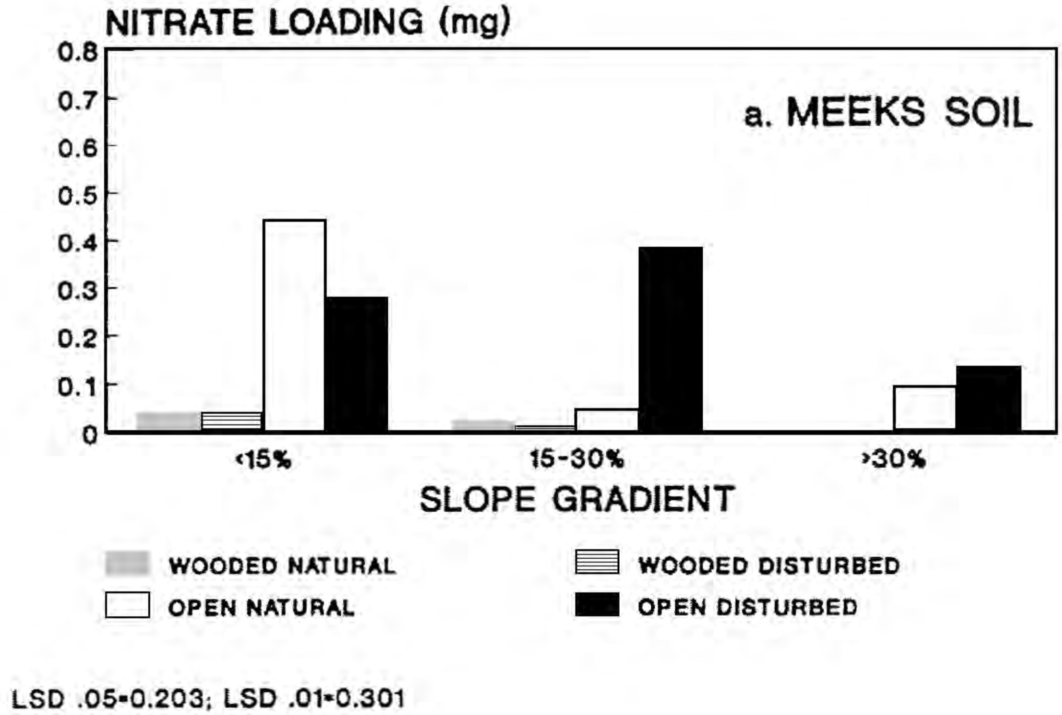
Surface runoff is a primary nutrient transport mechanism, so it is important to understand what areas are most vulnerable. Nitrate content in runoff from open areas has been found in greater quantities than in surface runoff from wooded sites (Figure 4-13). In contrast, conifer stands in the Tahoe basin have been found to be efficient at removing nitrate from precipitation (Naslas et al. 1994; Coats et al. 1976). When a wooded site was disturbed through litter removal or soil raking, the nitrate discharge increased, but not to the level of the open sites. Soil type was also significant in predicting nitrate levels but not as important as plot condition. On all sites, the early stages of runoff produced the highest levels of nitrate (Naslas et al. 1994). Summer rainfall and runoff also are a source of nutrients to Lake Tahoe. Sullivan et al. (1996, 1998) found that although total loading from summer precipitation may not be great, the runoff nutrient concentrations are often quite high. Construction or other disturbances should be scheduled to avoid periods of snowmelt runoff or summer storms to minimize nitrogen loading to the lake.

What is the effect of nutrient cycling in the watershed on transportable carbon, nitrogen, and phosphorous? How does system hydrology interact with nutrient cycling to influence nutrient loading?

Nutrient Reservoirs in the Terrestrial Watershed

There are several ecosystem components that serve as reservoirs (nutrient pools) for water and nutrients, such as carbon, nitrogen, and phosphorus. These can be broadly grouped into five categories:

- Vegetation—forest, shrub understory, meadow, riparian and, nitrogen-fixing/non-nitrogen-fixing plants;
- Forest floor—litter, duff, humus;



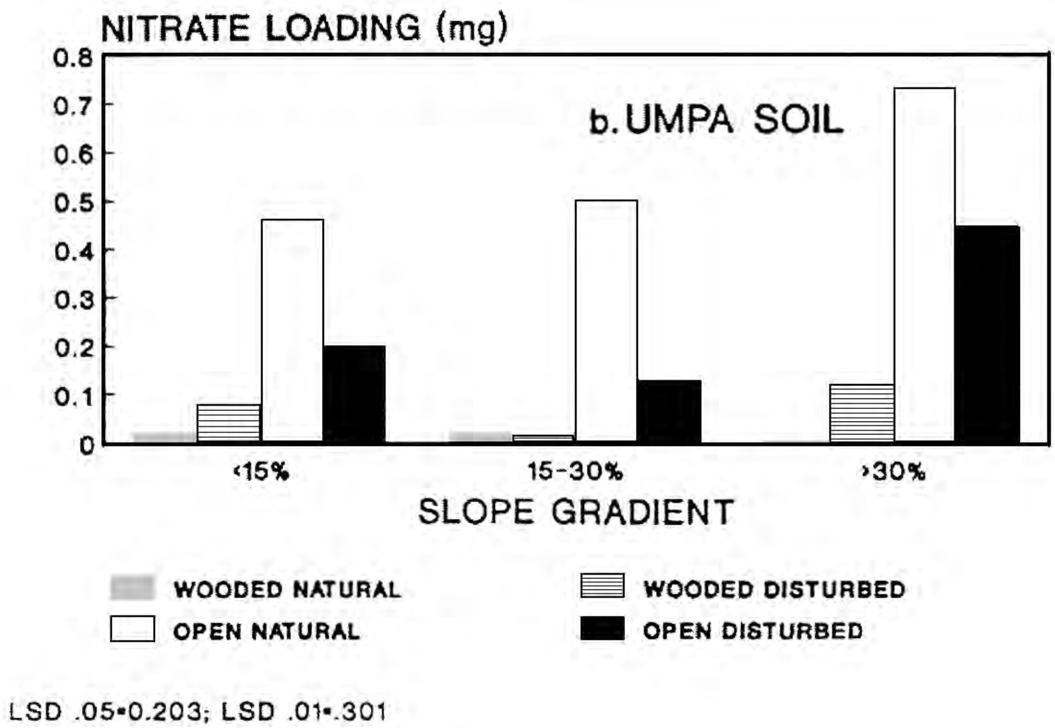


Figure 4-13—Nitrate loading in surface runoff from Meeks and Umpa soils during one hour of artificial rainfall application (from Naslas et al. 1994).

- Soils—granitic, volcanic, upland, riparian;
- System hydrology—soil water, streamflow, surface runoff, ground water, terrestrial/aquatic interface (hyporheic zone); and
- Stream sediments—primarily bedload, which moves a rate slower than that of channel flow.

Each of these reservoirs plays a key role in the cycling (source/sink interaction) of watershed nutrients. When linked with dynamic watershed processes, these reservoirs in conjunction with hydrologic response ultimately determine discharge water quality.

The terrestrial watershed nutrient pool in soils is generated and resupplied from both internal and external resources. When internal resources are inadequate for plant nutrient supply, nutrients are commonly imported from external sources, such as inorganic and organic fertilizer. Internal nutrient resources, however, are derived from within the ecosystem itself, be it a forest, a watershed, or a home. These resources include processes of mineral weathering, biological nitrogen fixation, acquisition from atmospheric deposition, and internal recycling from plant and animal residues.

Nutrient cycling is affected by temperature, vegetation, soil type, and presence of bacteria, organic matter, and soil oxygen (Hixson 1989). It affects the availability of nutrients for plant uptake and the nutrient reservoir available for transport and discharge. The transport of nutrients, particularly N and P, to Lake Tahoe unquestionably is an important cause of enhanced algal growth and decreased clarity.

Watershed Processes Affecting Nutrient Cycling and Transport

The Ward Creek watershed contributes only six percent of the annual surface runoff to the lake but is the fourth largest of the 63 watersheds in the basin. Its soils are derived primarily from andesitic and basaltic rock sources. Vegetation consists of conifers, meadow plants, and mountain alder. Coats et al. (1976) studied Ward Creek to evaluate the effect of soil disturbance on nitrogen concentrations in tributary discharge water. At the time of the study the watershed was relatively undeveloped, but logging and road construction had disturbed large areas. The study considered seven plots: unlogged, newly logged, red fir, old logged, alder, meadow, and an readability plot that had been raked and whose vegetation had been removed through herbicide application. All sampled areas were approximately 10^4 m^2. Their results showed that organic N content was consistently higher in the A soil horizon than the subsurface C horizon for all plot conditions. Furthermore, soil disturbance was found to increase the variability of organic N levels within a stand. The newly logged plots yielded more organic N in soil water extracts than did the study plots.

Precipitation collected throughout the winter in three separate meadows was analyzed for N content, thus N input from precipitation was determined. The unlogged plot removed almost all NO_3^--N added from the snowmelt. Soil water extracts from the undisturbed control plots contained little NO_3^--N. Those from beneath newly logged red fir and meadow plots, however, contained higher NO_3^--N. In older logged plots (eight years prior), there was a net release of NO_3^--N from the surface layers, but little was derived from the deeper C horizon. Soil water extracts from beneath the mountain alder plots contained very high levels of NO_3^--N. This was attributed to the N_2 fixation. NO_3^--N levels in the A and C horizons were positively correlated; when high in the A horizon it was also high in the C horizon. Tree basal area and C:N ratio correlated inversely with log (NO_3^--N). This shows that a heavy conifer stand with N-poor litter both strips the NO_3^--N from snowmelt water and inhibits nitrification.

Soil samples were perfused with either ammonium sulfate or distilled water for 30 days to determine if the addition of NH_4^+-N increased nitrification. It was found that the nitrification potential was high in the disturbed erodibility plot and low in the undisturbed unlogged plots. In the disturbed plots litter disturbance and vegetation removal may have created conditions favorable for heterotrophic mineralization. This would have increased the supply of NH_4^+-N available for biological nitrification and the release of NO_3^--N.

Even so, Coats et al. (1976) reported NO_3^--N loading into the lake from Ward Creek to be fairly small. It would appear that release of NO_3^--N from such disturbances as home construction can be mitigated fairly rapidly with prompt revegetation of the site.

Leonard et al. (1979) conducted a study similar to that of Coats et al. (1976). Their focus considered sediment nutrient flux into Lake Tahoe from Ward and Blackwood Creeks. Blackwood Creek is the third largest watershed in the basin and is similar in geology but substantially less vegetated than Ward (50 percent sparse or no cover for Blackwood versus 31 percent for Ward). Estimated inorganic N inputs to the watershed via atmospheric deposition in 1973 and 1974 were one to two kg/ha, based on measurements taken at Ward Valley (Leonard et al. 1979) (not equivalent to direct deposition on the lake surface, as discussed above for Lake Tahoe's nutrient budget). Estimated nitrogen fixation contributed 10 to 20 kg/ha.

Summer and early winter stream NO_3^--N levels were very low in the absence of rainfall. Later, during winter and spring, NO_3^--N in tributary discharges were higher in response to snow and snowmelt. In areas of mountain alder vegetation, there was a steady flux of NO_3^--N into the stream water during fall and early winter. The flux, however, is believed to change depending on the amount of rainfall received earlier in the year. Given enough rainfall, NO_3^--N would flush early into the stream water with baseflow. Concentration and flux patterns were similar. NO_3^--N was transported into the streams during periods of heavy spring runoff, and most of the annual load entered the stream from a single storm. It is interesting to note that NO_3^--N flux did not correlate with streamflow volume. This suggests that flux was controlled by the release of NO_3^--N from soil to stream water, as well as from direct runoff.

In this study (Leonard et al. 1979), organic N analysis was not performed, and NH_4^+-N levels were below detection (<5 μg/L). However, other studies have reported higher levels of NH_4^+-N in various tributaries of the Tahoe basin (Glancy 1973). LTIMP data collected between WY 1989 and 1993 show that NH_4^+-N concentrations are typically less than 10 μg/L, but they can reach 20 to 50 μg/L and occasionally even greater than 75 μg/L. Leonard et al. (1979) believed that the unreliability of analytical methods was reflected in the variability of organic N levels in Tahoe tributaries in the literature existing at that time. Since the mid-1980s, the LTIMP data for dissolved Kjeldahl-N has been very reliable relative to those much earlier measurements.

Dissolved organic/colloidal nitrogen fractions recently have been reported to be the major N form discharged from the leaching of intact soil cores taken from the Incline Creek watershed (Harlow 1998). Further study is needed to estimate accurately the mobility of colloids throughout the Tahoe basin. Although Marjanovic (1989) also reported high dissolved organic-N loading rates, it is as yet unclear what fraction of the total nutrient budget is affected by colloid transport or what mechanisms may affect their transport and bioavailability. This study (Harlow 1998) examined only the leachate mobility of nutrient-bound colloids and not the potential for colloids to actually reach the lake or to enhance the growth of algae.

Wetlands, artificial or natural, traditionally have been considered to function as a sink for sediment and nutrients. Settling basins or wetlands (natural or artificial) are designed to remove coarse sediment (sand and silt), initially through sedimentation and filtration and ultimately through vegetative uptake. Vegetation is also particularly effective at lowering the flow velocity such that particulate settlement is facilitated. Nitrogen removal is generally very efficient. Wetland plants with associated bacteria provide a site for the rapid uptake and removal of N, primarily through denitrification. Denitrification also can function as a primary sink for nitrogen. In an undeveloped headwater area on eastern slopes of the Sierra Nevada, denitrification was found to remove almost all of the available nitrogen (Brown 1987; Melgin 1985). Another meadow near Lake Tahoe demonstrated denitrification rates twice that of the input rate from rainfall (Greenlee 1985). The most important factor in nitrogen removal was found to be residence time. The slower the flow and the longer the residence time, the more efficient the N removal.

The influence of such physical factors as channel morphology on hydrology adds opportunity for denitrification because of the increased expanse and temporal extent of saturate soils within the root zone or riparian vegetation. Decaying roots provide the carbon source that supplies energy to denitrifying bacteria that thrive where water tables fluctuate slightly but frequently. The abundance of available water for riparian vegetation adds to the opportunity for plant growth and nutrient uptake. At Lake Tahoe, Morris et al. (1980) found that as tributary flow, which was nutrient-rich, passed through an undisturbed wetland/stream riparian zone, 74 percent of the total-N, 86 percent of the total-P, 72 percent of the total iron, and 84 percent of the suspended sediment was removed.

In the late 1980s, an artificial wetland was constructed near Lake Tahoe to receive runoff from a fertilized athletic field (Reuter et al. 1992). During WY 1988, the wetlands received 873 m^3 of surface runoff. Water samples were collected at points of inflow and outflow to evaluate the removal of sediment and nutrients, and TKN was sampled during periods of high and low runoff. At low runoff (December 1987 and April-May 1988), TKN in the inflow was greater that the outflow because of the longer residence time. TKN was removed during low runoff but was discharged during high runoff. TKN was exported when inflow concentrations were less than 500 μg N/L, but above that level the wetland functioned as a sink.

The wetland was very efficient at removing nitrate from the inflow runoff. Removal efficiency (in concentration) was 93 percent and 85 percent in both winter and summer, respectively. Final discharge concentration was close to that found in Lake Tahoe (<10 to 15 μg N/L). Ammonium was not removed, and the wetland often acted as a source. This may have been due to the immature state of the vegetation. The root systems may not have been established enough to give proper O_2 levels for nitrification to occur. Low nitrification rates would increase the inefficiency of removal of both ammonium and TKN.

Presumably the rate of nutrient capture relates inversely to the rate of water transport. As a sediment detention basin fills up, the rate of water transport through a pond increases. Eventually it will become sufficiently full that vegetation will encroach onto the deposited sediment. Then it will act more as a stream with an accessible floodplain. Thus the export of the sediments and their stored nutrients may not be a big hazard, but the decreased functionality of it for nutrient capture is. If there is a mechanism for stored sediment and nutrient export, that ought to be described.

Reuter et al. (1992) found that particulate P was well removed by the artificial wetland. Since particulate P and sediment are commonly associated, it is not surprising that suspended sediment and turbidity also were greatly reduced. Percent removal for suspended solids ranged from 85 to 89 percent. Even at low flow rates, however, clay-sized particles in complex with particulate P can remain in solution. These finer particles are the most difficult to remove from solution. Consequently, particulate P, soluble P, and sediment levels need to be continually monitored in artificial wetland systems because it is not clear how these wetlands will respond with age.

Recent research (Rhea et al. 1996; Harlow 1998) suggests that natural riparian zones can, in fact, function as a source of N and P as a result of nutrient cycling processes. For example, a newly constructed sedimentation pond initially might be quite effective in removing particulate nutrient forms, such as P. Once overgrown with vegetation, however, biotic nutrient cycling processes may well contribute rather than remove N and P. A sediment and nutrient analysis on wetland discharges would be most helpful in determining if wetlands actually reduce nutrient loading on a long-term basis. Finally, accumulated sediments and associated P would be vulnerable to extreme upper watershed events. High flow discharges could easily flush accumulated sediment and nutrients directly into the lake. Project protection and maintenance are essential.

Johnson et al. (1997) studied nutrient fluxes in Little Valley and Sagehen Creek, in the eastern Sierra Nevada. They found that organic N fluxes were generally greater than inorganic fluxes. Inorganic N and P from snowpack under a canopy was immobilized in the soil, with a flux of only 1 to 15 percent of the input. Decomposition under snowpack is responsible for a pulse of nutrients during snowmelt. NO_3^--N stream water pulses occurred during the winters of low snowfall years in both Little Valley and Sagehen Creek watersheds. Soil solution NO_3^--N was low during snowmelt, indicating that the NO_3^--N did not pass through the soil. In years with average precipitation, no stream water increase in NO_3^--N would be expected at these two sites.

On the other hand, mineralization and nitrification do not appear to be large contributors of N to stream water from forest watersheds in the Tahoe basin. Nitrification occurs in forest soils, but it is generally limited by pH, the natural supply of NH_4^+-N, and decomposing litter (Coats et al. 1976). On the other hand, mineralization and nitrification can be significant in areas that have been disturbed or are covered with logging slash (Leonard et al. 1979). Other localized sources of N are related to N_2 fixing vegetation such as mountain alder trees (Goldman 1961).

Nutrient cycling occurs on a localized scale. This makes it difficult to predict the effects of nutrient cycling on basin-wide nutrient loading. Nitrogen transformation processes are well understood but highly variable. Phosphorus cycling also is highly variable but less well understood. No information was found on transportable carbon, and dissolved/suspended colloidal transport should be studied further. This is a potentially significant method of nutrient transport and could pose a real barrier to nutrient management in the Tahoe basin.

Lake Tahoe Basin Ground Water Quality, Nutrient Loading and Evidence of Land Use Impacts

The difference between stream and ground water discharge lies in the method of Lake entry. Streamflow discharge is rapid, and initially spreads out into the Lake, primarily as a result of discharge turbulence. Ground water discharge is comparatively slower, and enters the Lake in a much more diffuse manner. This ground water flow is more likely to have an effect on the littoral (shore) zone sediments, stimulating benthic growth. Ground water also can enter a stream as baseflow. Depending on the level of ground water discharge, baseflow contributions can be a significant component of tributary nutrients loading (Woodling 1987).

Several studies have been completed that add to the knowledge of ground water quality and nutrient loading in the basin (Loeb and Goldman 1979; Loeb 1987; Thodal 1995, 1997; Tyler and Ramsing 1998). These studies have indicated that elevated levels of nutrients are present in some ground waters and that ground water may contribute significant nitrogen and phosphorus to the lake. The following focuses on the results of these studies with particular emphasis on evidence that links land use to ground water quality and nutrient loading.

Ward Valley—In 1975, Loeb and Goldman (1979) did geophysical studies and ground water nutrient monitoring in the Ward Valley watershed along the west shore in order to estimate the total ground water flow and associated nutrient loading into Lake Tahoe. They estimated the amount of ground water flow to be 410 x 10^7 L/yr, which was about 16 percent of the flow carried by Ward Creek and 10 percent of the total precipitation in the watershed. Well chemistry data collected from four wells in the watershed indicated that the average ground water nitrate concentration was 162 μg/L and that the average soluble reactive-P concentration was 73 μg/L, while ammonium concentration was below the level of detection (<15 μg/L). Based on these values, the amount of nutrient loading from ground water into the lake was calculated. Ground water nitrate loading from Ward Valley was estimated to contribute 49 percent of the total watershed nitrate loading to the lake and 44 percent of the soluble reactive-P loading. This study indicated that while the volume of ground water entering the lake may be small relative to other sources (e.g., stream water), the amount of biostimulating nutrients entering the lake may be substantial.

Loeb and Goldman (1979) also found much higher levels of nitrate in two wells than could be accounted for by stream or precipitation sources. They speculated that the additional nitrate probably came from urban development in Pineland (about 200 homes), where, until 1970, all the houses leached their sewage into the permeable soils and substrata.

They speculated also that the impact of ground water nutrient inputs on eutrophication of the lake could be significant. Streams enter the lake at discrete points, with stream water and associated nutrients rapidly extending out into the lake; in contrast, ground water from Ward Valley enters Lake Tahoe at a much lower velocity and over a wide sediment-lake interface. The movement of ground water and associated nutrients would enrich the littoral benthos, stimulating the productivity of the benthic algal and bacterial communities.

Upper Truckee River and Trout Creek—Loeb (1987) did a more intensive study of ground water quality in three major basin aquifers: the Upper Truckee River, Trout Creek, and Ward Creek. Geophysical studies of aquifer characteristics and wellwater monitoring were combined with studies of seepage and algal growth to estimate nutrient loading and to determine whether an association between ground water inputs and nearshore algal growth could be demonstrated. The results from well water monitoring showed an association between ground water nutrient levels and land use. Water quality data was collected from 49 wells and springs within the three study aquifers. In Ward Valley, nitrate concentrations in ground water increased two to 10 times as it flowed toward Lake Tahoe through the developed (Pineland) portion of the watershed. In the Upper Truckee River and Trout Creek aquifers, higher nitrate concentrations were similarly found nearer the lake and developed areas than at sites upgradient in the watershed. The highest average nitrate concentrations in the south shore aquifers were observed in the developed area in the vicinity of the "Y" where highways 50 and 89 join. These findings led to the conclusion that ground waters were being contaminated with nitrate as they moved toward Lake Tahoe through developed or disturbed areas of the watershed.

Interestingly, chloride concentration showed similar trends as nitrate in the Upper Truckee River and Trout Creek aquifers; that is, samples with high nitrate also had high chloride. However, concentrations of ammonium and phosphate did not show similar trends as nitrate. Ammonium concentration was very low in all three aquifers, and phosphate was low in the south shore aquifers and only slightly higher in the Ward Creek aquifer. Loeb (1987) identified several potential sources for high nitrate and chloride, as follows:

- Fertilizers and increased nitrification following land disturbance or land with impervious surfaces are sources of nitrate;
- Exfiltration from sewer lines or old septic leach fields could contribute both nitrate and chloride; and
- De-icing salt used on highways in the winter is a source of chloride.

Ground water flow modeling indicated that discharge from the ground waters of the Upper Truckee River and Trout Creek aquifers to Lake Tahoe was approximately 170 x 10^7 L/year. Ward ground water flow calculated by Loeb and Goldman (1979) was 410 x 10^7 L/year. Therefore, Ward ground water flow was estimated to be 2.4 times the amount of ground water flowing into the lake from the Upper Truckee River and Trout Creek aquifers combined.

Ground water nitrate N and soluble reactive P loading to the lake were estimated to be 525 kg N/year and 185 kg P/year from Ward Creek and 799 kg N/year and 26.64 kg P/year from the Upper Truckee River and Trout Creek aquifers. The amount of nitrate and soluble phosphorus contributed by ground water could be a significant proportion of the total watershed input (stream plus ground water) of these forms. Nitrate loading from Ward Creek ground water was estimated to be about 60 percent of that from ground water and streams combined, while the contribution of nitrate from the Upper Truckee River and Trout Creek aquifers was estimated to be 20 percent of the watershed nitrate. Ground water phosphorus loading was 44 percent of watershed loading (stream water plus ground water) in Ward Creek but only two percent of loading in the Upper Truckee River-Trout Creek watershed.

Nutrients carried by ground water into Lake Tahoe become focused into the nearshore region of the littoral zone. It has been in this region of the lake that visible signs of differential nutrient availability and accelerated eutrophication have been observed in the form of increased amounts of attached algae (periphyton) (Loeb 1980; Loeb et al. 1986). Loeb (1987) monitored attached algal growth in the nearshore zone adjacent to the aquifers to see whether impacts of ground water flow on algal growth could be detected. Seepage meters were used to try to determine ground water flow rates at the sediment-lake interface, and sediment interstitial water was measured to estimate quality of ground water seeping into the lake. Seepage flow rates and quality then were compared with in-lake measures of algal growth to determine whether an association existed. Loeb also did periphyton and phytoplankton bioassays, which tested algal response to nitrogen, phosphorus, seepage, and well waters.

It was difficult to demonstrate definitively a direct association between algal growth in the lake and ground water input; however, the results did provide evidence for such an association. Only limited success was achieved by directly measuring seepage because the flow rates were near the limit of detection for the method and because of methodological difficulties. The amount of algal growth was not found to be correlated with seepage or seepage nutrient loading. However, this was due, at least in part, to the confounding influence on algal growth of differential stream inputs of nutrients at the sites. An increased growth of periphyton for at least one site (Pineland, which is adjacent to the Ward Creek aquifer) was thought to have been due in part to ground water inflow. At Pineland elevated levels of periphyton growth were found, along with positive seepage of ground water containing elevated N and P concentrations. Bioassays showed that Pineland interstitial water was stimulatory to periphyton growth. In addition, nutrient enrichment bioassays showed that periphyton growth was highest when nitrogen and phosphorus were added in combination rather than singly. Increased periphyton growth at this site was probably due, in part, to seepage of ground water containing both nitrogen and phosphorus. Loeb (1987) indicated that ground water inputs, along with other important sources, such as streams and nonchannelized runoff, are significant in regard to nearshore algal production. The effect of nutrients entering through this ground water pathway was thought to be an increased production of periphyton in the littoral zone.

The results from Loeb (1987) also demonstrated the water quality variability of ground water systems that may interact with Lake Tahoe. Due to the diversity of geologic and physiographic settings and the different degrees of development and types of land use, extrapolation of results from studies of individual aquifers to other parts of the basin may not be appropriate (Thodal 1995). Moreover, in order to evaluate the ground water component of the nutrient budget for Lake Tahoe, it is necessary to characterize the hydrogeologic setting of the entire basin and to identify the features that are related to the distribution of nutrients in ground water (Thodal 1995).

Hydrogeology of the Lake Tahoe Basin—From 1985 to 1987, a study was done to determine the quality and nutrient content of ground water and to characterize the hydrogeologic setting of the Tahoe basin (Thodal 1995). Concentrations of nutrients in the aquifers were found to be generally low, but certain areas that had particularly high nutrient concentrations were identified. Anthropogenic sources were possible at these sites, but a definitive link could not be made. Dissolved nitrate concentrations at least two orders of magnitude greater than concentrations reported for Lake Tahoe were measured in samples from wells on golf courses and near an abandoned septic tank system. However, historical data indicate that there were comparable nitrate-nitrogen concentrations in these areas as early as 1961, predating the golf courses. According to Dr. J. Unsicker (1999), several factors may have contributed to this finding. The riparian areas that became golf courses probably were used for livestock gazing, and livestock waste may have entered the ground water. Alder trees or other nitrogen-fixing species may have contributed. Analytical techniques for nitrate measurements have changed significantly and now have lower limits of detection.

Concentrations of organic nitrogen and ammonia nitrogen greater than 1 mg/L were measured in ground water in the vicinity of a resort that historically relied on a septic tank system for wastewater disposal and that also has a riding stable. This area also is underlain by carbonaceous alluvial deposits that could contribute these species of nitrogen to the ground water system.

Orthophosphate was generally low and not distinguishable as associated with particular land uses. For nonmacronutrient species, chloride concentration was elevated in three wells near US Highway 50, indicating ground water quality may be locally affected by leachate from road salt.

Thodal (1995) also estimated ranges of annual nutrient loads possibly transported to the lake through three aquifers that extend along 1.3 miles of the 19 miles of shoreline in the study area. A wide range in potential loading of nitrogen, phosphorus, and iron was found, which was a result of uncertainty associated with aquifer geometry and hydraulic properties and local variability in concentrations of nitrogen and iron. Nevertheless, the nutrient loading estimates indicated that ground water is a plausible pathway for solutes to enter the lake.

With a need for information on the overall contribution of ground water to the nutrient budget of Lake Tahoe, from 1990 to 1992 the USGS, in cooperation with TRPA, initiated a basin-wide ground water monitoring program to evaluate the role of ground water in processes of nutrient loading to the lake. Historical data describing ground water flow and quality were reviewed and a ground water quality monitoring network was designed and operated to provide information on the relative significance of ground water to the nutrient budget of Lake Tahoe. The results of this study are presented in Thodal (1997).

Thodal (1997) found that nitrate-N was the dominant form of nitrogen in ground water samples, that it represented 100 percent of nitrogen at 17 of 31 sites, and that it averaged about 85 percent of measurable nitrogen. A large range in filtered nitrogen concentrations was observed (<0.020 to 12 mg/L), and several sites had very high soluble nitrogen suggesting contamination associated with land use. Five well sites contained nitrate concentrations higher than 1 mg/L, up to a maximum of 12 mg/L (Nevada Maximum Contaminant Level is 10 mg/L). Two sites with high filtered nitrogen are in the South Lake Tahoe urban area and downgradient of an area historically used for spray-disposal of treated sewage effluent. Other areas of high nitrogen included two observation wells on golf courses and an observation well near a resort that historically relied on a septic tank leach field system for domestic waste disposal. Concentrations of phosphorus and iron did not range as much as nitrogen concentrations, and no relation to land use was apparent from the data. Tritium activity in samples of well waters indicated many of the aquifers had been recharged since 1952. Relationships between recharge dates and nutrient concentrations need to be examined.

This study also looked at ratios of nitrogen isotopes in samples of ground water from several of these high-nitrogen sites in an attempt to determine their sources. Variation in the ratio of isotopes of nitrogen ($^{15}N/^{14}N$) have been used in other studies to determine sources of nitrogen in the hydrologic cycle (Heaton 1986) and to distinguish ground water contaminated with fertilizer N from that contaminated from human or animal wastes (Exner and Spaulding 1994). The results of these analyses were in general not conclusive, they indicated that N ratios in high nitrogen areas were within a range characteristic of oxidized soil nitrogen; however, one of the golf course well sites was in the range that could indicate a synthetic fertilizer source. Elevated concentrations of soluble nitrogen suggest that mechanisms capable of accumulating soil nitrogen may exist at these sites. Possible mechanisms include nitrogen fixation or evaporative concentration of nitrogen, or alternatively the soil nitrogen could be from a combination of N sources, such as from synthetic fertilizer and sewage effluent.

The mean cationic composition of the ground water was 46 percent calcium, 27 percent sodium, 23 percent magnesium, and four percent potassium. The mean anionic composition was 81 percent bicarbonate, 11 percent chloride, four percent sulfate, three percent nitrate plus nitrite, and one percent fluoride. These values are based on a relatively small number of samples, and the results were variable from well to well. The median nitrate-nitrogen concentration was 0.14 mg/L in ground water, but 0.014 mg/L for Lake Tahoe. Nitrate accounted for approximately 85 percent of the total nitrogen in the samples, while organic nitrogen and ammonium was 10 percent and five percent, respectively. Total P from filtered water samples ranged from 0.021 to 0.40 mg/L, with a median of 0.058 mg/L. Approximately 55 percent of total P was orthophosphate, and 42 percent was organic P.

Thodal (1997) used a combination of approaches to estimate ground water discharge to the lake for the entire basin. Ultimately a figure of 40,000 acre-ft/yr (from the top 50 feet of saturated basin fill deposits) was used as a first approximation of discharge. Nutrient contributions from ground water then were estimated by multiplying the mean concentrations of nutrients by the estimated volume of water discharged. This approach indicated that the ground water contribution of nutrients to the lake was 60 tons/yr of nitrogen, four tons/yr of phosphorus, and two tons/yr of soluble iron (see section on Lake Tahoe nutrient budget). Thodal underscored that there is a considerable degree of uncertainty in such estimates of mass loading, due to the small amount of available information on geologic boundaries, hydraulic gradient, and hydraulic conductivity. Assumptions that a mean concentration is representative for the entire basin is an additional uncertainty, especially considering that the number of sample sites were relatively small (32) and appeared to contain several polluted wells. Continued study related to these factors will help refine loading estimates and identify links to land use. However, these estimates do indicate ground water is a potentially significant source of nutrients to the lake.

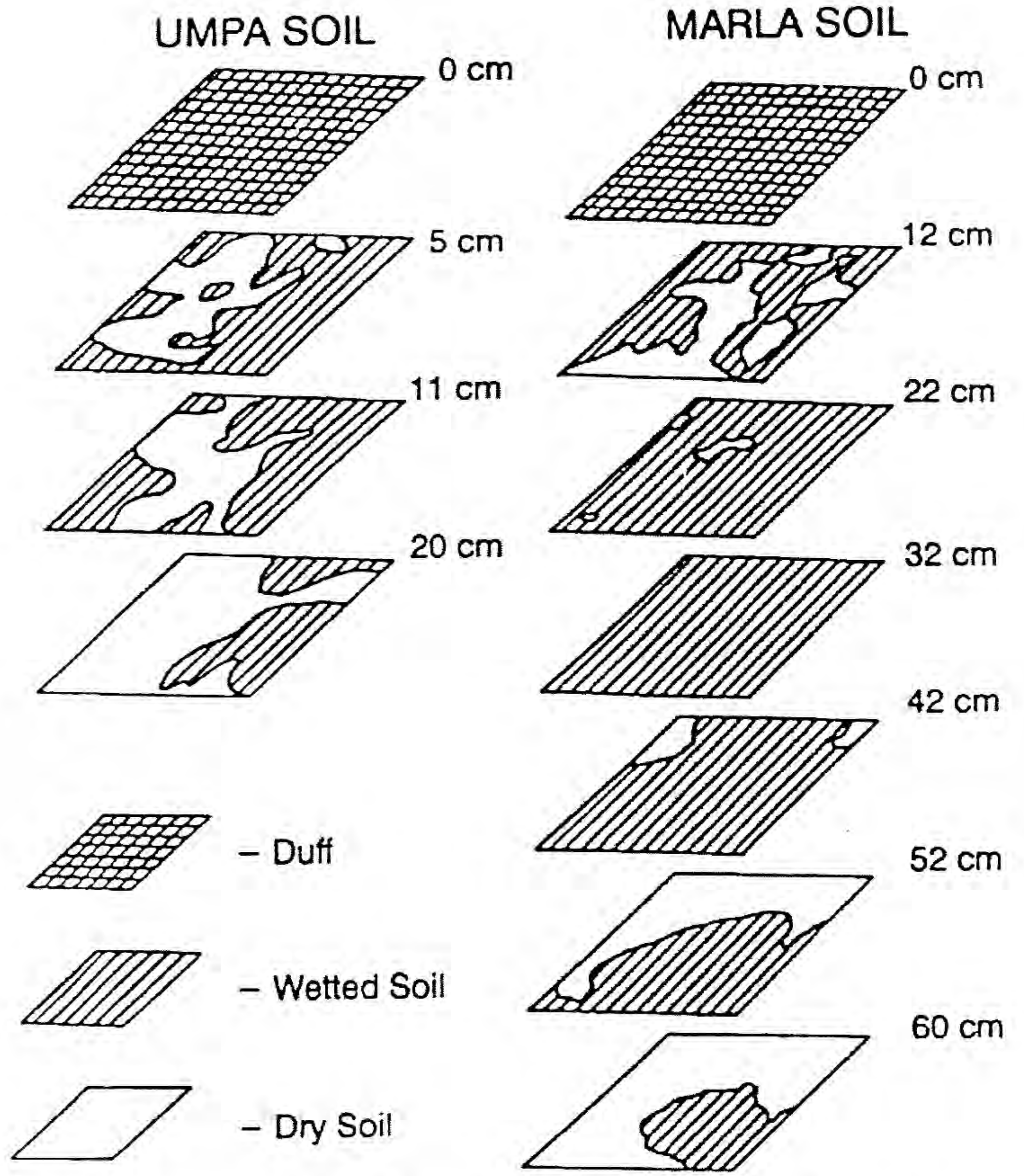
Factors Affecting Mobility in the Shallow Subsurface Environment

Many soils of the Tahoe basin exhibit preferential infiltration and subsurface water flow. Preferential flowpaths can act as a shortcut to the ground water; as such, nutrients tend to bypass direct contact with the soil matrix, which generally would enhance nutrient removal from the percolate. Water-repellent soils tend to exhibit greater preferential flow during drier seasons. Furthermore, predominant preferential flow paths (Figure 4-14) are especially evident in finer textured soils of the Sierra Nevada (Burcar et al. 1994). Under conditions of preferential flow, nutrients are more likely to enter baseflow in forested areas immediately adjacent to tributaries and the lake itself. Nitrate was found to be more mobile in granitic soils than volcanic soils under conditions of normal matrix flow. Preferential flow paths in finer-textured volcanic soils could be responsible for more rapid transport of nitrate to the ground water.

In a study of stormflow source in a small mountain watershed, McGraw (1998) employed a combination of artificial rainfall observations and computer modeling to develop an understanding of potential subsurface flow from the riparian zone to the Upper Incline Creek. Results indicated that for events with wet antecedent soil conditions the estimated subsurface contribution ranged from eight percent to 36 percent of the total streamflow increase (i.e., due to subsurface water flux), while for those events with dry antecedent conditions the subsurface contribution ranged from 32 percent to 72 percent of the total streamflow.

Colloidal nitrogen and P were studied in Incline Creek to determine their role in subsurface nutrient transport. Rhea et al. (1996) created artificial rainfall to collect surface runoff and subsurface infiltrate on gentle (<15 percent) and moderate (>15 percent) slopes. The dominant water extractable N and P forms contained in soil extracts were colloidal rather than inorganic. Colloidal N increased in the soil following precipitation, indicating mobility. Colloidal P decreased following winter at the upper watershed locations but not at lower locations.

Marcus et al. (1998) examined leached soil nutrients from three classes of vegetation. Leachability of the organic matter showed that colloidal organic matter is significant in nutrient transport. Riparian sites were found to contain the most inorganic and colloidal nitrogen from soil extracts compared to forested and nonforested sites (Figure 4-15). Nitrogen-fixing mountain alder may have contributed to the higher nitrate levels on the riparian site. The elevated inorganic and colloidal nitrogen probably reflects the depositional nature of the site under the influence of riparian vegetation



Late summer–early fall wetting patterns in forested areas by depth.

Figure 4-14—Preferential flow patterns observed in Umpa and Marla soils following artificial rainfall application (from Burcar et al. 1994).

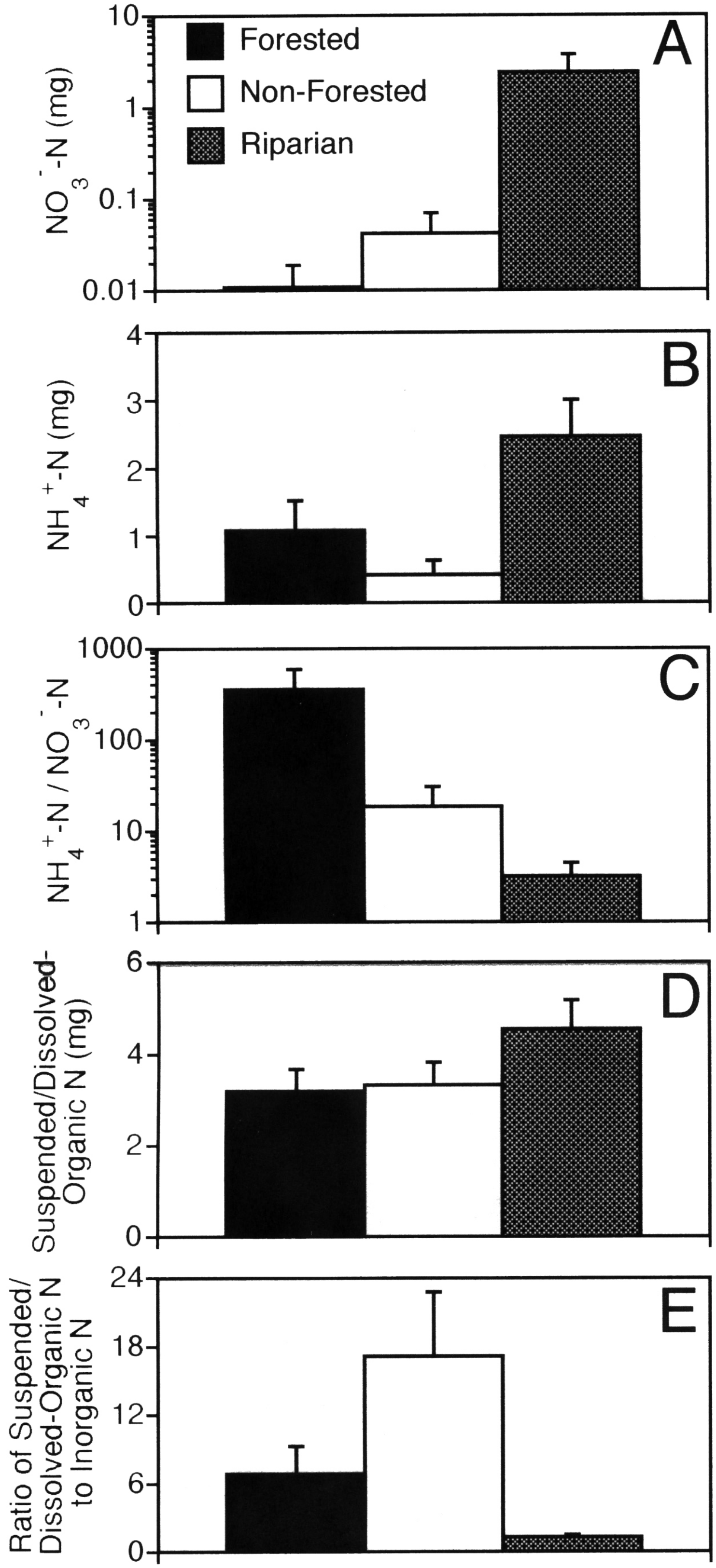


Figure 4-15—Cumulative inorganic and dissolved organic nitrogen in leachate from undisturbed forested, nonforested, and riparian soil cores (from Marcus et al. 1998).

and flood energy dissipation over deposited sediments and the history of vegetative uptake.

Harlow (1998) also found that local vegetation has an effect on the nutrient leachability. Sites near nitrogen-fixing mountain alders were examined to determine local increases in nitrogen. The alder did contribute nitrate to the soils, and the colloid forms were mobile in samples taken during leaching experiments. Transport of these colloids is a potentially serious but poorly understood mechanism. Colloidal N did not correlate with percent organic matter in the soil, indicating that the colloids are associated with nonorganic material.

While nitrogen fixation by alder would be an addition of N to the Lake, loss of N via denitrification in or near saturated soils would be a subtraction. Riparian woody vegetation is needed in some situations to provide channel roughness to reduce velocity and soil binding or coarse woody debris to keep soil in place where it is critical for stream hydraulics and hydrology. Although some other woody plants could provide these functions at some levels and in some places, alder is clearly adapted to this role quite well. Removal of woody riparian vegetation obviously would have serious consequences for water quality immediately and for decades to come.

MTBE in Lake Tahoe Ground Water and Drinking Water Wells

One of the most dramatic examples of the sensitivity of basin ground waters to contamination from human activities has been the recent finding of methyl tertiary butyl ether (MTBE) in several public water supply wells in the South Lake Tahoe area (Fogg et al. 1999). Eight of the South Tahoe Public Utility District's (STPUD) 34 wells have been shut down following detection of MTBE in water samples, and four additional wells have been shut down due to proximity of MTBE plumes to the wells. MTBE is a highly soluble fuel additive that has been labeled a possible cancer-causing agent. Significant sources of MTBE ground water contamination are leaky underground fuel storage tank systems and spills around fueling facilities. Once introduced into the aquifer MTBE moves freely with the ground water and can persist for long periods. The use of MTBE in fuels apparently began to grow in 1990 as a result of federal Clean Air Act amendments, and the first well closures as a result of MTBE contamination occurred in 1997. Unlike nutrients in ground water, for which specific sources may be difficult to pinpoint, MTBE can be traced directly to sources of fuel leakage in the watershed overlying the aquifer.

Continuing Studies

Studies of ground water in the basin are continuing. The University of Nevada Reno is studying ground water hydrology, ground water quality, and seepage to the lake in the Incline Creek watershed. This study included ground water monitoring in the vicinity of golf courses, as well as in the nearshore area, among other sites. Tyler (1998) discusses aspects related to hydrology. The results related to ground water quality should be available in a thesis in progress by F. Ramsing (Tyler 1999). The hydrogeology and ecology of Pope Marsh recently were studied by C. Green at the University of California at Davis (Green 1998). Changes in water inputs into the marsh have occurred probably as a result of surface water diversions around development, and data also suggest that ground water pumping affects water levels in certain areas of the marsh during drought. These changes can exacerbate the affects of drought on the marsh. While his study focused on hydrology, Green also collected some samples for ground water quality analysis, including from an area below a controlled burn. Interestingly, he found elevated levels of nitrate in these samples and observed an algal bloom in the burn area. This suggested that the burn area was the source; however, because no preburn ground water data were available, it is difficult to definitively attribute high nitrate concentrations to the burn (Green 1998). Finally, USGS is continuing its ground water studies in the basin, including studies of interactions between ground water and tributaries (Thodal 1997). These studies should further greater understanding of the ground water component of the watershed.

Summary

The information gathered so far in several ground water studies has provided evidence that human activities and land use practices within the basin can increase the levels of nitrogen or other contaminants in the ground water. This evidence has included the following:

- Findings of higher nitrate levels in well waters in more heavily developed sections of the basin;
- Findings of high nitrogen in wells located near suspected sources of anthropogenic nitrate, such as abandoned septic tank systems, areas where treated effluent was sprayed, and golf courses where fertilizers are used;
- Evidence of elevated levels of chloride in wells near US Highway 50, which is suspected to have originated from highway de-icing; and
- Recent findings of MTBE in several South Lake Tahoe wells from leaking underground storage facilities or from surface spills.

Additional information is needed to relate ground water impacts (and magnitudes of impact) to specific sources and land uses.

There are indications that ground water indicate ground water is a potentially significant source of nutrient loading to the lake. When considered in the annual budget of nutrient loading to the lake, ground water may contribute 14 percent of the nitrogen and four percent of the phosphorus. If most of the ground water phosphorus is loaded in a dissolved form, its relative contribution to biologically available phosphorus will be much higher. Much of the impact from ground water is likely focused in the nearshore area of the littoral zone. Bioassays have indicated that algal (phytoplankton and periphyton) growth is stimulated by the addition of ground waters that contain nitrogen and phosphorus. Ground water inputs, along with such other important sources as streams and nonchannelized runoff, are likely to be significant in regard to nearshore algal production. Continued study related to such factors as geologic boundaries, hydraulic gradients, and hydraulic conductivity will help to refine loading estimates and to identify links to land use.

What are the major characteristics of sediment transport in tributary flow to Lake Tahoe? What is known regarding the important sources of this material?

Perhaps the most significant factor connecting watershed land use and geomorphology hydrology to water quality is the change in peak flow events that comes with such changes to land use as urbanization (Hammer 1972; Booth 1990). These changes frequently upset natural dynamic equilibria in stream reaches and lead to drastic alteration of stream channel morphology, such as channel incision. "Regardless of whether the incision is caused by external or internal controls, the presence of the incision indicates a threshold of stability that has been exceeded" (Schumm 1977). This is especially true in alluvial streams where the connection to a floodplain is critical for energy dissipation, watershed hydrology, and nutrient capture and storage. Once incised, the stream is very likely to export stored nutrients as its energy becomes unleashed to rapidly erode banks that are decreasingly protected by riparian vegetation (Zonge and Swanson 1996). This sets in motion a chain of events that has been described by many (e.g. and Schumm et al. [1988], Harvey and Watson [1986], Van Havern and Jackson [1986], Swanson and Myers [1994], Pritchard et al. [1993, 1998], Rosgen [1994, 1996], Simon [1989]), including Butt et al. (1998), for work in the Tahoe basin.

"The causes of incision are highly variable but the response of incised channels, regardless of scale, follows a very similar pattern, which suggests that their evolution can be predicted" (Schumm 1977). Using the stream classification metrics of Rosgen (1997), one could easily envision a stream cross section becoming approximately 20 times larger after crossing a threshold of incision and before recovering. However, the relative magnitude of incision depth, and therefore crosssection enlargement, will vary with substrate, distance upstream from effective base level, and sometimes the rate of channel widening. Channels that are straightened at the time of incision tend to deepen more than channels that remain sinuous because the steeper gradient increases velocity and cutting before reaching a new gradient controlled by downstream base level. Once initiated, the degree of incision and the rate of channel widening often have little to do with on-site management until the enlarged channel width allows for the reduction of shear stress sufficient for a floodplain and riparian vegetation at the new lower level.

Incised channel widening represents considerable export of stored alluvium and the incumbent nutrients. Alluvial lands have been forming as floodplain depositional material, often with the influence of wetland or riparian vegetation; therefore, much of the stored sediment, especially in surface horizons, is fine grained. The increased nutrient concentration and bioavailability represented by fine grained and organic material, and the capture of soluble nutrients by vegetation often causes these soils to be quite fertile. Loss of this stored alluvium and its store of plant nutrients represents both on-site degradation and downstream eutrophication. Butt et al. (1998) provides more detailed information about the riparian focus areas of many Tahoe basin watersheds, including Big Meadow, Blackwood, Burke, Burton, Cold, Marlette, Meeks, Slaughterhouse, Taylor, Third, Trout, Ward, Watson, and Zephyr Creeks, and the Upper Truckee River. They found problems with channel incision in all but Burke, Meeks, Taylor, Watson, and possibly Zephyr Creeks.

Fortunately, the process of incised channel widening leads back to the opportunity for sediment deposition and nutrient retention under the influence of riparian vegetation and energy dissipation across the new floodplain and with increasing sinuosity (Harvey and Watson 1986; Rosgen 1997; Swanson and Myers 1994; Prichard et al. 1998).

Early Field Studies

One of the most comprehensive investigations of sediment source in the Tahoe basin was performed by Glancy (1988) at Incline Village. He measured streamflow and sediment loading for the five principal tributaries of Incline Village, a drainage area of 17.8 square miles. From 1970 to 1973, 31,000 tons of sediment was transported to the lake, 75 percent of which was gravel and sand, 15 percent was silt, and 10 percent was clay. Glancy found a poor relationship between fine sediment load and discharge. Most of the sediment was transported during snowmelt. The sediment yield was three to 930 tons per square mile for undeveloped regions and 26 to 5,000 tons per square mile for developed regions. The developed areas had approximately ten times the sediment yield. Much of this sediment yield was attributed to specific point sources: road cuts, unpaved roads, culvert outfalls, and rerouted drainage systems.

Undeveloped areas that experienced flash floods had continued elevated sediment yields, probably as a result of bank erosion and channel instabilities. A flash flood in 1967 on Second Creek transported 75,000 tons of sediment in one afternoon. Glancy describes area/altitude relationships for Third and Incline Creeks, two of the larger tributaries. Third Creek has substantial high altitude regions. Its hydrology is much more subject to flash floods than is Incline Creek, which transported most of its sediment during the less frequent large flow events. Glancy attributed this to high altitude snowmelt occurring quickly at the end of the snowmelt season. Glancy hypothesized that sediment pickup was occurring along the main channel, as there is no longer melting snow at lower elevations to transport sediment to the channel. He suggests measures to reduce sediment yield, including dispersing rather than concentrating runoff, minimizing land surface disturbance, concentrating land surface disturbance to resistant areas and during low runoff times, and restabilizing disturbed areas.

Sediment Inputs From LTIMP Streams

A preliminary analysis of the annual sediment loads and hydraulic discharge and average annual concentrations for the nine LTIMP tributaries from WY 1989 to 1996 is presented below. Rowe (1998) also provided a discussion of sediment load from WY 1989 to 1996. The east shore tributaries (Glenbrook and Logan House) had an order of magnitude lower sediment loading than the west shore tributaries (Ward, Blackwood, and General), the northeast shore tributaries (Third and Incline), or the Upper Truckee River. This is primarily due to a rain shadow effect. By the time weather fronts reach the east shore they have already lost most of their moisture. With less precipitation there is less flow for erosion and transport of sediment. The Upper Truckee River is the largest contributor of sediment, followed by Incline Creek and Blackwood and Ward Creeks. In terms of concentration, Third Creek was exceedingly high, at a level of 616 mg/L. Incline and Blackwood Creeks were the next highest, at 97 and 71 mg/L, respectively. Glenbrook, Trout, and Ward Creeks and the Upper Truckee River were intermediate (29 to 43 mg/L), with Logan House Creek at 19 mg/L and General Creek the lowest, with an average suspended sediment concentration of 15 mg/L. These data reinforce the contention that General Creek is functioning as an undisturbed tributary despite its location on the wetter west side. Furthermore, the extremely high concentrations of total suspended sediment emanating from Third Creek suggests that a more careful survey of this watershed be conducted. Concentrations for particulate-P were also much higher in Third Creek over this same period, confirming the need for further investigation.

Stream	Total Suspended Sediment (mg/L) (annual average)	Flow (10^8L) (total annual)	Load (MT) (total annual)
Trout	29	275	797.5
Upper Truckee	42	787	3305.4
General	15	134	201.0
Blackwood	71	295	2094.5
Ward	43	209	898.7
Third	616	64	3942.4
Incline	29	11	31.9
Glenbrook	29	11	31.9
Logan House	19	3	5.7

The bulk of sediment is delivered during the spring snowmelt, but rainstorms can cause high runoff at any time. Therefore, sediment transport is variable, depending on the streamflow velocity and volume. Leonard et al. (1979) studied sediment nutrient flux into Lake Tahoe from Ward and Blackwood Creeks. Blackwood Creek is the third largest watershed in the basin and is similar in geology but substantially less vegetated than Ward Creek (50 percent sparse or no cover for Blackwood versus 31 percent for Ward). In Ward Creek suspended sediment was generally below detection (1 mg/L) during the low winter and summer flows of 1973. However, with the November rains of 1973 came peak sediment concentrations of 2,000 mg/L as a result of channel scouring. Following the scouring episode, sediment decreased to 200 mg/L (1974), 800 mg/L below previously recorded spikes of 1,000 mg/L before scouring. Of the bottom two reaches of Ward Creek, one is in a state of rapid adjustment and the other is in a state of accelerated channel erosion, due to channelization and adjustment to loss of floodplain access because of road encroachment. The first 790-meter reach was classified as a Rosgen F3 (1996), having little or no accessible floodplain within twice maximum bankfull depth. The next reach was classified as an unstable B3, even though B3 channels are frequently stable. In several places along this 6,780-meter reach the stream is responding by cutting into valley wall material. Protecting the floodplain and terrace edge from further development are important priorities (Butt et al. 1998).

In 1975, sediment concentrations in Blackwood Creek were twice as high as those in Ward Creek, probably due to the lack of vegetation and steep slopes. Diel patterns were exhibited in both creeks for streamflow and suspended sediment. Peak sediment levels in both creeks tended to precede the peak streamflow, then dropped rapidly afterward. In the water years of 1973 and 1975, over 95 percent of the sediment transported was associated with the spring snowmelt. However, in 1974 heavy rains in November, January, and July carried 50 percent of the total sediment load with 40 percent of the annual runoff. Sediment size distributions were as expected—silts at low flow and mostly sands when the suspended sediment levels were over 20 mg/L. Based on 83 samples, the ratio of silt to sand was approximately equal. In samples with large sediment concentrations, clays were detected up to levels of 25 percent, but most had very small amounts of clay. Despite the potential importance of fine-grained sediment particles to Lake Tahoe water clarity (Jassby et al. 1999), few data are available on the size distribution of sediment in runoff. It is important that these measurements be incorporated into future monitoring.

A percentage of the sediment reaching the lake enters directly via flow from zones intervening tributaries rather than first entering a tributary. The sediment contribution from these intervening areas may be large because they are at low elevation, are highly developed, and cause runoff to be channelized. At low elevations a larger proportion of precipitation falls as rainfall rather than as snow; importantly rain has more erosive energy than snow. As recommended for nutrients, a much better understanding of sediment load from urbanized intervening zones will be critical for purposes of management. As discussed below, development can increase sediment loading substantially. LTIMP monitoring has identified watersheds that are major sediment sources.

Sources of Sediment Within a Watershed

The most significant sources of erosion in the Tahoe basin are eroding channel banks, rill and splash sources on unvegetated steep lands, and roads and urbanizing areas. Hill and Nolan (1987) constructed a sediment budget for four watersheds at Lake Tahoe: General Creek and Blackwood Creek on the west side and Glenbrook Creek and Edgewood Creek on the east side. A sediment budget is an accounting of sediment inputs from all source areas within a watershed. Using a variety of techniques—river crosssections, erosion pins, erosion boxes—Hill and Nolan quantified the different erosional processes operating in the watersheds. They inferred that 70 percent of stream total suspended sediment was coming from streambank and streambed erosion on low order channels.

Leonard et al. (1979) performed an extensive nutrient and sediment analysis of Ward Creek. Detachment and transport was evaluated from bank erosion in the lower stream elevations, splash and rill erosion at high elevation on unvegetated steep soils, and forested land contributions. Forested soils were not found to be major sources of sediment. Bank erosion was the greatest source of sediment in Ward Creek in water years 1973 to 1975. A downstream monitoring station measured two to four times greater suspended sediment and 1.5 times the streamflow of the upstream monitoring stations. Enhanced stream flow presumably was derived from ground water or overland sources through low gradient, low sediment-producing areas. The increase in sediment was out of proportion with the streamflow and indicates that the stream channel itself is a primary contributor of sediment to the lake.

Glancy (1988), working on five principal creeks in Incline Village, Nevada, suggested flash flooding and roadways as the largest sediment sources. A flash flood on Second Creek delivered 75,000 tons of sediment in a single afternoon. Glancy found that sediment yields from developed areas averaged ten times those from undeveloped areas in Incline Village. Flash flooding can produce sediment loads to the lake 10 to 100 times greater than average annual sediment loading. Such events are not common, but the effects can be devastating and can cause channel instability that contributes to future erosion problems. There is evidence of major flooding in the basin during the 1870s, which would account for floods following recorded logging and fire episodes. Such an environment would be at severe risk, and the floods probably resulted in major sediment discharges into the lake.

Another source of information on sediment sources within watersheds is the LTIMP multistation data as analyzed from WY 1991 to 1996 (Stubblefield and Reuter, unpublished). For Ward, Trout, and Incline Creeks and the Upper Truckee River there are yearly sediment yields for three locations: an upper headlands station, mid-watershed, and the mouth of the creek. Stations are the same as those used by Hatch (1997) (see section above on stream phosphorus). The data indicate large differences in the spatial pattern of sediment loading between watersheds (figures 4-16 to 4-19). For example, comparison of Ward Creek and the Upper Truckee River, shows that at least 50 percent of the sediment load in high and low flow years is coming from the headwaters of Ward Creek, an area of steep unvegetated soils. The Upper Truckee River has much smaller relative contributions from its headwaters, a heavily forested region. Incline Creek also shows most of the sediment contribution from developed areas lower in the watershed. On Trout Creek the pattern has been complicated either by Lake Christopher, an in-river lake, or by the wetland that was constructed in place of this waterbody. Sediment concentrations are lower downstream, suggesting a sediment trapping effect. Discussion of

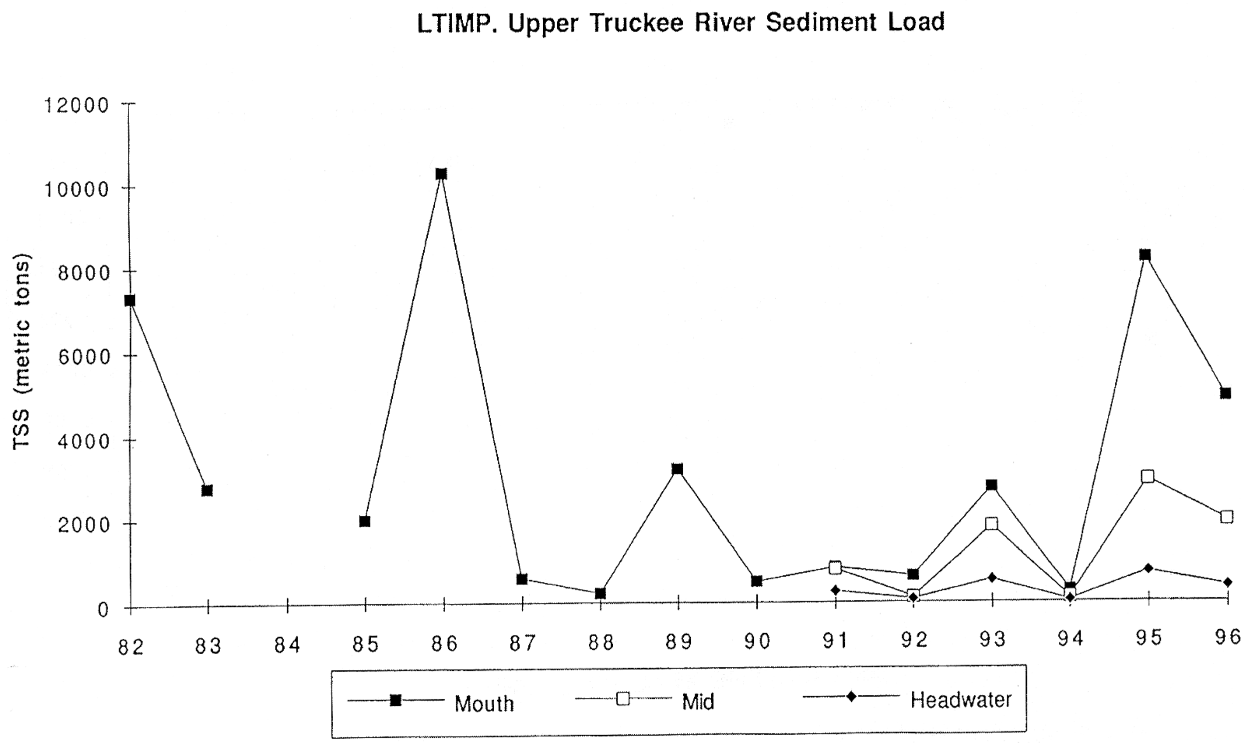


Figure 4-16—Annual load of total suspended solids in the Upper Truckee River. In recent years, sampling at multiple stations distinguishes TSS loads in certain subwatersheds.

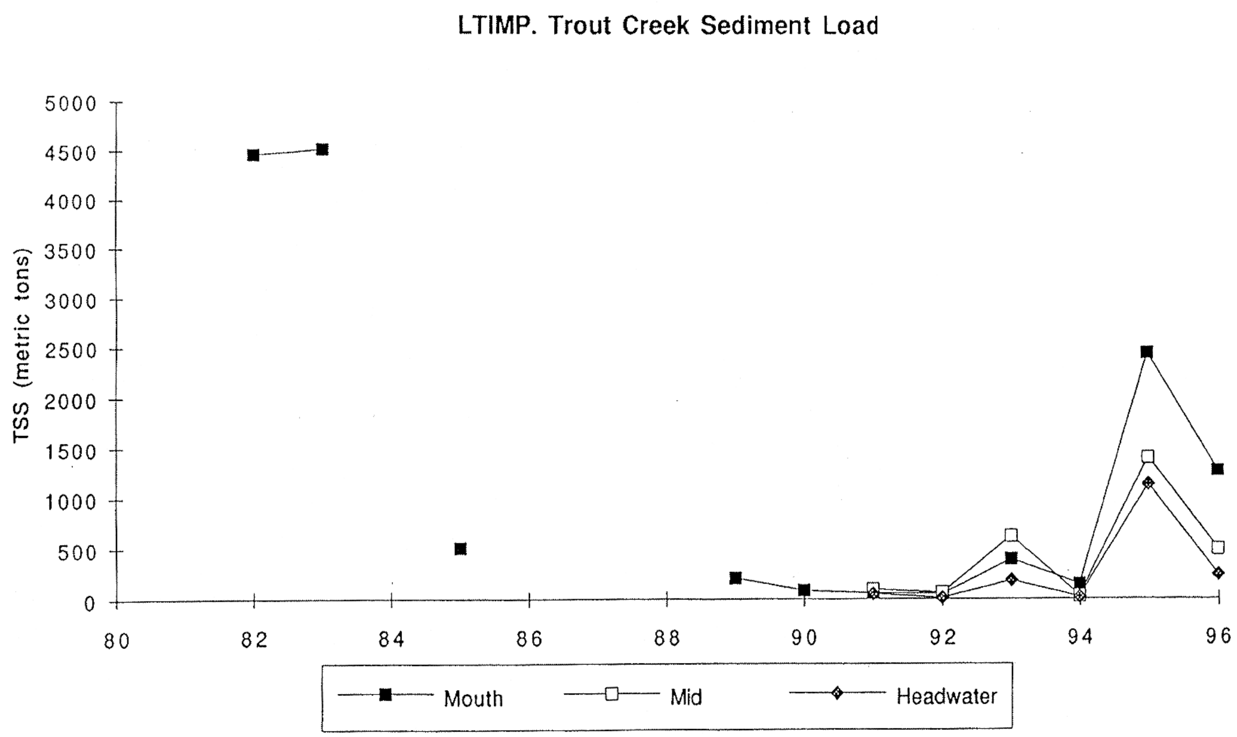


Figure 4-17—Annual load of total suspended solids in the Trout Creek.

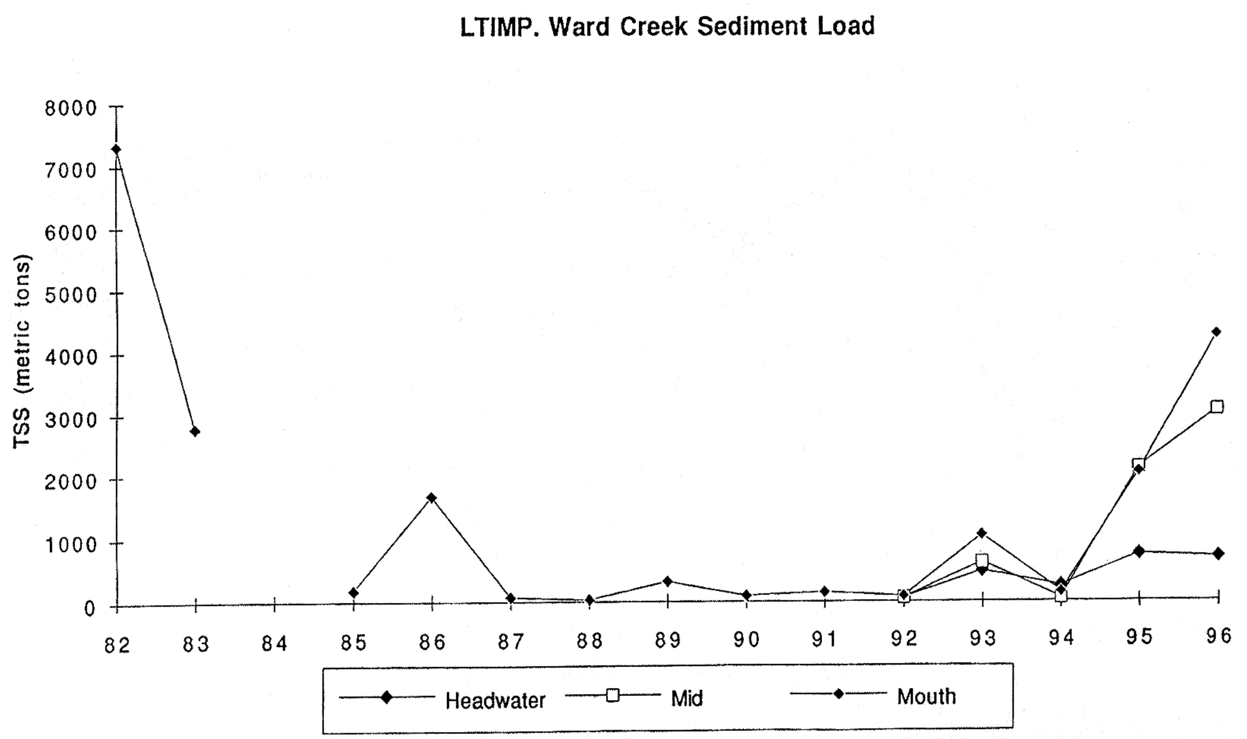


Figure 4-18—Annual load of total suspended solids in the Ward Creek.

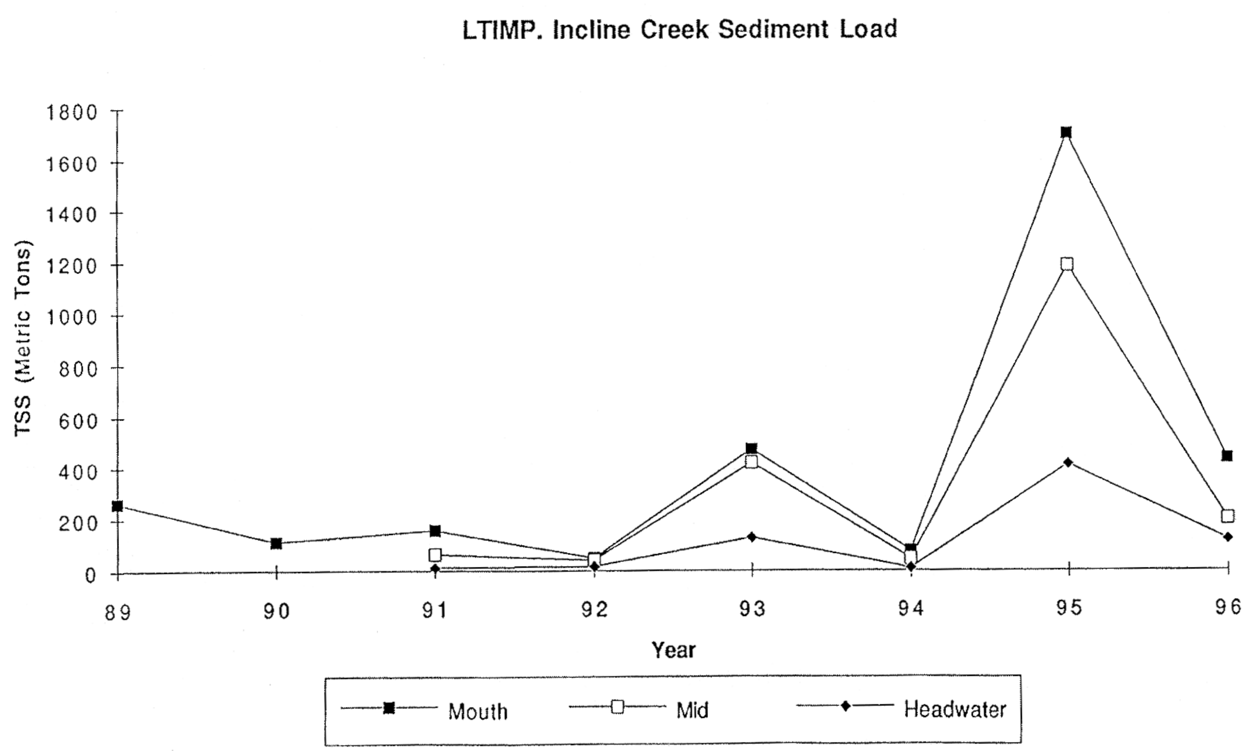


Figure 4-19—Annual load of total suspended solids in the Incline Creek.

sediment sources leads to discussion of the next question: evidence for the links between land use and watershed geomorphology and sediment loading. As observed for phosphorus, the greatest differences between stations within a single watershed occurred during high water years, such as WY 1995. Both WY 1993 and WY 1995 indicate that sediment load within the Ward Creek watershed is minimal between the middle and lake mouth stations. Again, for the Upper Truckee River, the pattern was the opposite; i.e., large amounts of sediment enters the river between the upper and middle stations, as well as between the middle and lake mouth station. For Trout Creek, a sizable portion of sediment load was observed between the middle and lake mouth stations.

Evidence Linking Watershed Characteristics to Sediment Load

Some degree of erosion is natural, especially on steep slopes. Erosion potential also is affected by soil type, litter layer, overland flow, slope, vegetation, and presence or absence of land disturbance (Guerrant et al. 1991; Naslas et al. 1994). Land development and lack of revegetation also can be major factors in sediment loading. Blackwood Creek had double the Ward Creek sediment loads in 1975. Compared to Ward, Blackwood has less vegetation and greater soil disturbance. High elevation, steep soils are subject to splash and rill erosion and mass wasting. This is well illustrated in the upper reaches of Ward Creek (Leonard et al. 1979). The developed watersheds (Blackwood and Ward) have sediment discharge levels that are an order of magnitude greater than less developed Meeks Creek and General Creek watersheds. This large amount of sediment is undoubtedly also the result of such natural factors as steep slopes and not solely from development.

Approximately 70 percent of the basin runoff is derived from granitic soils (Court et al. 1972). Indeed, erosion is very common on nonvegetated granitic slopes. Vegetation can minimize the kinetic effects of rainfall, reduce particulate detachment, remove sediments from runoff, and enhance infiltration (Gray et al. 1980). Blackwood Creek is characterized by a unique combination of high rainfall and steep, sparsely vegetated watershed slopes that make it a high sediment-producing tributary. Because of the high sediment loads, the lower channel is being aggraded. Furthermore, channel straightening has destroyed the flood pattern, which allows sediment deposition over a broad area. Now this sediment ultimately washes into Lake Tahoe (USDA Forest Service 1989b).

Blackwood Creek is destabilized by a combination of floodplain development, channelization, and channel incision. Furthermore, future channel incision is likely in some places and would exacerbate channel stability and bank erosion/water quality problems. Upland disturbances and in-channel construction projects have had a variety of mostly detrimental effects. However, headwater reaches appear to be quite stable. "The abundance of beaver activity on this stream appear(s) to be insufficient to stabilize it against the forces of high sediment supply and fluctuating runoff" (Butt et al. 1998).

Using the LTIMP database, Byron and Goldman (1986) found a significant correlation between percent disturbed of high/low hazard land in a watershed that is either covered or disturbed and sediment loading. They also found a correlation between road density/drainage density and the relative sediment loading to a watershed.

As mentioned above, Glancy (1988) found developed areas of the Incline Village watershed to be contributing 10 times more sediment than undeveloped areas. Within developed areas most sources of sediment input to Incline Creek could be traced to specific point sources. Roadways were the most obvious and widespread source of fluvial sediment. Within undeveloped areas the largest sediment source appeared to be flash floods and the elevated sediment yields resulting from flood-disrupted channel stability.

From 1972 to 1974, Kroll investigated sediment discharge from highway cut-slope in the Tahoe basin (Kroll 1976). At the same time, using continuous discharge measurements and frequent sampling of suspended sediment, Kroll estimated the suspended sediment contribution to Lake Tahoe from seven creeks (the Upper Truckee River, Trout Creek, Grass Lake Creek, Eagle Creek, Meeks Creek, Quail Lake Creek, and Dollar Creek). These study basins represented 45 percent of the total water inflow to the lake. This 1972 to 1974 period was compared to a more extended database for six of these tributaries, which extended from 1961 to 1974.

The estimated sediment loading between 1961 to 1974 from the seven tributaries was 6,400 MT, of which 2,100 MT was fine sediment (>63 microns). For the period 1972 to 1974, loading from these tributaries was 4,900 MT, with 1,800 MT as fine sediment. For both periods, the fine sediment accounted for 30 to 40 percent of the total. Kroll estimated that the average discharge rate of fine sediment into Lake Tahoe from all streams was 4,000 MT/yr. He determined that 90 percent of the sediment load to Lake Tahoe in stream channels was suspended load rather than bedload.

To measure sediment from highway cut-slopes, Kroll installed 16 gutterflow stations and measured discharge and sediment load once or twice a week. During the spring snowmelt, he made measurements twice daily and occasionally hourly. The measured sediment discharge reflected not only erosion from highway cut-slopes but also sand applied for traction control on curves and hills. He found a mean annual sediment discharge of 272 MT, of which 27 MT was fine sediment; 180 MT of this was discharged at a single location, which had received large amounts of applied sand and gravel. The estimate of annual fine sediment discharge from cut-slopes along California state highways in the Tahoe basin was less than 91 MT, or approximately only two percent of the fines discharged by all tributary streams. Kroll stresses that not all the highway sediment will necessarily be transported to and deposited in the lake. Also, Kroll did not attempt to look at erosion and sediment transport in such places as roadside earthen-channels. Nevertheless, this 1976 report provides an excellent base from which to conduct a more detailed study.

Results from other watersheds may be informative in establishing the link between land use and sediment yield. Hollis (1975) found that urbanization increased the magnitude and frequency of floods in a watershed. This would increase bank erosion and sediment yield. Trimble (1997) found that two thirds of the sediment yield from urbanizing basins in Los Angeles was from bank erosion. Booth and Jackson (1997) monitored 80 urbanizing watersheds in the greater Seattle area and found that when the effective impervious area of a watershed exceeded 10 percent of the total watershed area, the creeks became highly unstable, having long reaches of eroding banks. The frequency and magnitude of floods increased as well. The results of these studies suggest that the following processes may be in operation at Lake Tahoe: urbanization is increasing the impervious cover in watersheds; increased impervious cover reduces infiltration rates so runoff reaches streams much more quickly; this reduced residence time results in larger and more frequent high flows; frequent high flows repeatedly damage stream banks before they have a chance to revegetate, resulting in high sediment yields.

Localized Sources of Sediment and Watershed Improvement Plans

A series of watershed improvement plans have been written for Lake Tahoe watersheds to assess current conditions, including localized sources of erosion. Between 1989 and 1994, each watershed was examined for obvious signs of erosion along system roads, trails, paved roads, and channels. Watershed slope, soil/rock types, and vegetation quantity and quality were noted, and each stream channel was evaluated for stability. This inspection of a watershed is tremendously important in determining actual conditions because models do not always correctly predict locations of severe erosion. (The watershed improvement plans are available through the USDA Forest Service, 1989a-c, 1990a-f, 1991a-g, 1992a-h, 1994a-c.) However, the riparian vegetation and channel form study described by Butt et al. (1998) provides more detailed information about the riparian focus areas of many of these watersheds, including Big Meadow, Blackwood, Burke, Burton, Cold, Marlette, Meeks, Slaughterhouse, Taylor, Third, Trout, Ward, Watson, and Zephyr Creeks and the Upper Truckee River.

What is the water budget for Lake Tahoe and how might future regional warming scenarios affect precipitation and runoff in the Tahoe basin?

Dominated by the 156 km^3 volume of water in Lake Tahoe proper, the hydrology of the Lake Tahoe basin naturally plays the primary role in affecting the ecological state of the lake itself and the surrounding terrestrial environment. Lake eutrophication is the consequence of nutrient inputs from the atmosphere and watershed. Because most nutrients are carried to the lake or discharged from it by the movement of water, it is vital to quantify, as accurately as possible, the lake's water budget. The major components of a preliminary water budget are summarized below and were taken from Marjanovic (1989). A summary of four other Lake Tahoe water budgets is presented in Thodal (1997) and include McGauhey et al. (1963), Crippen and Pavelka (1970), Dugan and McGauhey (1974), and Myrup et al. (1979), who report very similar values. However, Marjanovic calculated direct runoff into Lake Tahoe from the 52 intervening zones, and this component is important with regard to nutrient and sediment discharge from these often urbanized areas.

	Flux ($10^6/m^3/y$)	Percent Contribution
Sources		
Stream runoff	468.0	56.6%
Precipitation	299.0	36.2%
Direct runoff	54.7	6.6%
Ground water	4.81	0.6%
Total	**826.51**	**100.0%**
Sinks		
Evaporation	508.0	61.1%
Truckee River outflow	315.0	37.9%
Diversions outside the basin	9.01	1.0%
Total	**832.01**	**100.0%**

This budget leaves only 5.5 x $10^6/m^3/y1$, or <1 percent unaccounted for. The data records used to prepare the table are characteristic of the period between the 1960s and approximately 1991 and are not representative of periods characterized by prolonged periods of extremely wet or dry conditions; however, the water budgets cited above include the period from 1901 to 1970. Diversions outside the basin consist of the water exported by sewage and diversion of 2.34 x $10^6/m^3/y$ from Echo Lake to the American River basin.

Thodal (1997) reported that a ground water contribution of 40,000 acre feet, or 32.4 x $10^6/m^3/y$, may be a good first approximation. However, uncertainty due to measurement and extrapolation are large enough to raise this estimate to >81 $10^6/m^3/y$ (Thodal 1997). While ground water represents a negligible portion of the overall water budget, the potentially high nutrient content of ground water inflows can have a significant impact on the productivity of the littoral zone of Lake Tahoe. Thodal further estimated that ground water discharge represents about 11 percent of the mean annual precipitation falling on drainage areas tributary to the lake and that about 34 percent of the mean annual precipitation could be returned to the atmosphere by sublimation from snowpacks, evaporation of precipitation prior to recharge, and ground water discharge by phreatophytes (plants that obtain water from the water table).

Most of the precipitation in the Lake Tahoe basin falls as snow between October and May and runs off as snowmelt in May and June (Marjanovic 1991; Shelton 1992). Because the lake area itself is a large percentage of the basin's area, a correspondingly large portion of the water (36.2 percent) enters the lake in direct precipitation as snow or rain.

Nearly all the streams in the Tahoe basin lie on bedrock, with the exception of the south shore area, and some small aquifers associated with the lower reaches of some streams. While Loeb (1987) found that the aquifers for the Ward Creek, Trout Creek, and Upper Truckee River watersheds were sloped toward the lake (implying a net flow into the lake), some recent studies in the Pope Marsh area of the south shore indicate that under the influence of water pumping and seasonal effects, the net flow in some areas may be from the lake into the near-shore water table (Greene 1998; Fogg 1999).

Long-term Climate Change

Lake Tahoe exhibits evidence of dramatic responses to climate change in the past (Lindström 1990) and will continue to do so in the future. One likely mode of change involves the Tahoe basin's response to global warming and its effects on the regional water budget and sediment and nutrient dynamics. Shelton (1992) points out that in regions where snowmelt is a significant component of runoff, such as Lake Tahoe, shifts in the relative amounts of rain and snow and in the timing of snowmelt due to warmer temperatures may change runoff patterns.

Frontal weather systems from the Pacific Ocean deliver over 75 percent of the watershed's precipitation between November and March, much of it as snow (Shelton 1992). Topography plays an important role in the spatial distribution of precipitation and in determining whether the winter precipitation occurs as rain or snow. Lower elevations receive about 500 millimeters (mm) of annual precipitation, but the upper elevations on the west side of the watershed receive about 1,500 mm.

Though the global circulation models (GCMs) on which Shelton's predictions rest have improved since his original work (Shelton 1992), the fundamental conclusions remain the same—that global warming (or more generally, climate change) could profoundly change the magnitude, timing, and form of precipitation and hydraulic discharge in the Tahoe basin.

Shelton chose to deal with the uncertainties of the available GCM models by investigating cases of the temperature (T) increasing by 1, 2, or 3 °C in combinations with precipitation (P) changes of 0, +/-10, and +/-20 percent. From among these he found that the case of T + 1 °C, P + 20 percent increased annual runoff over the historic amount by 25 percent, while the case of T + 3 °C, P-20 percent decreased annual runoff by 33 percent, with the other cases falling in between.

However, keep in mind that predicted annual averages do not reflect the much larger seasonal changes predicted in this study; seasonal variations were generally much larger than changes in annual averages. For example, the historical runoff pattern for the Upper Truckee River peaks in May, followed by June and April, accounting for 59 percent of annual runoff. In the case of T + 3 °C, P-20 percent, the maximal runoff period was shifted to the January to March winter period and accounts for 62 percent of the annual runoff. Spring runoff is reduced by 76 percent compared to the historic record. Summer (June to September) declines to a meager 10 percent of the historical amount, and fall (October to December) is changed little.

The monthly estimates of runoff for the Upper Truckee River reveal the influence of the seasonal pattern of precipitation; a decrease in the proportion of winter precipitation that falls as snow, and an earlier and faster spring snowmelt. Changes in the volume of the snowpack and in the timing of snowmelt tend to accentuate the wet-dry climatic regime of the region. A serious consequence of these changes is a seasonal redistribution of runoff away from the spring months and toward the winter months. For instance, in the T + 3 °C, P-20 percent scenario, the change in peak flow is a three-month shift from May to March.

Climate change can have a significant effect on runoff in the Tahoe watershed because small changes in temperature and precipitation have an amplified effect on runoff. The overall impact of a warm, moist future climate would be to increase annual runoff by as much as 25 percent. The runoff regime would be modified modestly, with the major change being an increase in winter runoff. A warm, dry future climate in the region would reduce runoff by 33 percent. Peak runoff would occur three months earlier in the year, and four months each year, would experience increased runoff compared to current amounts. This change in regime results from an increase in the elevation of the snowline and a decrease in the winter snowpack.

The hydroclimatology of the Tahoe basin plays a significant role in maintaining the distinctive clarity and blue color of Lake Tahoe. Streamflow delivers sediments and nutrients that act as fertilizers for phytoplankton and attached algae in the lake (Goldman 1989). Sediment and phytoplankton in turn increase light scattering and absorption, reducing clarity and changing the color of the lake. Strong seasonal streamflow enhances the erosional ability of runoff and concentrates into a few months the stream's capacity to deliver sediments and nutrients to the lake.

Issue 2: Reduction of Sediment and Nutrient Loading to Lake Tahoe using Best Management Practices, Restoration, and Other Management Techniques

With contributions from Kyle Comanor, Charles R. Goldman, Steve Goldman, Scott H. Hackley, Alan C. Heyvaert, Shari Silverberg, Sherm Swanson, and John Warwick

What management/restoration approaches are currently being used in the Tahoe basin?

Most management and restoration activities focus on mitigating erosion potential and reducing sediment and nutrient discharge to Lake Tahoe. Soil and slope stabilization, water conveyance structures, infiltration systems, constructed wetlands, and sediment retention structures all are believed to function in this capacity (Fenske 1990). The objective in this issue is not to address each individual land use practice or BMP used in the Tahoe basin; as stated below, this is needed but beyond the scope of this assessment. Rather, in this section an initial framework from which future activities might proceed is established.

Examples of General Management/Restoration Approaches

Incised rivers provide a great challenge to implementing various restoration/improvement/ stabilization solutions. The following information is key to restoring natural stability and function to incised rivers (Rosgen 1997):

- Understand the cause of the incision (entrenchment);
- Analyze watershed conditions that may not only indicate cause but may provide the solution;
- Select the stable stream type associated with the landform/valley type;
- Understand the restoration objectives and make sure they are compatible with the natural stable morphology;
- Obtain data from reference reaches of the stable stream type to be emulated;
- Understand the evolutionary tendencies of rivers and recognize where the particular river is in relation to its potential end-point of equilibrium;
- Select restoration priorities that allow the stream to speed up the process of natural stability along the evolutionary sequence;
- Avoid working against the natural probable state of the river, or "patching in place;" and
- Integrate geomorphology, engineering, biology, and botany into the restoration solution.

Soil compaction during road construction and timber harvest reduces infiltration and enhances surface runoff. Increased surface runoff results in greater particle detachment and soil surface erosion. One way to alleviate soil compaction is to avoid operating heavy equipment when soils are wet; however, this alone is insufficient. Other practices include mitigating unnecessary or temporary roads and trails by tillage and constructing small-scale water retention levies to enhance infiltration, thereby reduce runoff and erosion. For timber thinning, such alternative techniques as helicopter or over-snow harvesting are often used.

Slopes from road cuts are often unstable and subject to mass failure. Wood or rock retaining walls, coupled with improved drainage, are used to facilitate slope stabilization. Channel bank erosion is relatively common in the basin. Management for stream restoration includes creating meanders to reduce flow velocities, reshaping the banks, removing debris, and revegetating newly exposed banks. Waterbars, culverts, and diversion ditches are used to slow water flow and to direct it into sediment retention basins or constructed wetlands.

Increased infiltration significantly decreases direct nutrient and sediment transport to streams. Trenches, dry wells, and infiltration basins are used to collect surface runoff and to divert it into the subsoil layers. This practice is quite effective in reducing surface runoff and sediment transport; however, the effectiveness in terms of reducing ground water nutrient transport is much less certain. Homeowners in the basin are required to construct retaining structures, such as timber walls, revegetation projects, and rock-lined infiltration trenches, along drip lines below eaves and other impervious surfaces. Homeowners are expected to mitigate the potential for erosion, sediment transport, and deposition from their lots (Tahoe Regional Planning Agency 1999).

Santini-Burton Act

Another strategy to mitigate impacts from development has been that of public land acquisition. The Santini-Burton Act allows environmentally sensitive lands to be purchased or exchanged and then managed in the public interest. Land exchanges and purchases via the Santini-Burton Act have increased national forest land in the Tahoe basin to 158,000 acres. The United States Forest Service now owns and manages approximately 77 percent of the basin. Significant portions of the Tahoe basin also are owned by the states of California and Nevada. Special effort is made to acquire those lands in stream zones and wetlands or that are otherwise environmentally sensitive. Public ownership allows for the preservation of sensitive land areas for recreational use and for controlled management and restoration. Development is kept at a minimum, and lands are continuously monitored for potential impacts (enhancement or degradation) on discharge water quality. It is not surprising that the Forest Service conducts most of the basin-wide management and restoration activities, including watershed restoration and fire management. Fire hazard reduction is a rapidly growing concern and includes removing dead trees and developing defensible space at the urban/wildland interface (Sierra Nevada Ecosystem Project 1996).

Integrated Management Approach

Many state, federal, and local government agencies play vital roles in managing watersheds and in implementing restoration and other improvement projects. In addition to the Tahoe Regional Planning Agency, both Nevada and California have very active programs for land acquisition, planning, site improvement, and large-scale management. The California Tahoe Conservancy (CTC) exemplifies a well-integrated program whose goals include preserving environmentally sensitive lands through acquisition, repairing disturbed land through erosion control grants, restoring degraded wetlands and watershed areas, facilitating the transfer of development rights from more environmentally sensitive areas to ones that are less sensitive, managing acquired lands toward the purpose for which they were obtained, protecting, preserving, and enhancing wildlife and the habitats that sustain them, and enhancing public access and recreational opportunities (CTC 1997).

While it is beyond the scope of this assessment to provide a detailed accounting of all the environmental restoration and related projects that have been done in the Tahoe basin, a summary of CTC activities provides an illustrative example. According to CTC statistics, since its inception in 1984, it has authorized the expenditure, either directly or through grants, of more than $150 million in site improvements and acquisitions. These include acquiring various interests in over 5,450 parcels, totaling greater than 6,450 acres, and implementing over 325 improvement projects. CTC (1997) provided the following summary of activities in terms of dollars spent since 1984 (values are expressed in millions of dollars):

Program	Improve-ments	Acquisi-tions	Total
Acquisition of environmentally sensitive lands		$69.4	$69.4
Land coverage		$4.9	$4.9
Management program and planning		$7.0	$7.0
Erosion control grants	$27.1	$7.9	$35.0
Stream environment zone and watershed restoration	$4.7	$1.4	$6.1
Wildlife enhancement	$3.1	$1.7	$4.9
Public access and recreation	$6.6	$16.2	$22.9
Total	**$48.7**	**$101.9**	**$150.6 Million**

According to the CTC, these efforts have resulted in 71 soil erosion control projects, revegetation of 115 acres, restoration of 85 acres of disturbed wetlands and meadows, construction of 78 miles of roadside drainage facilities, mitigation credit for over 2,200 public and private projects and transfer of coverage and other credits for 220 residential and commercial projects, increased public access to over 1.5 miles of lake frontage, and restoration of 1.340 acres of wildlife habitat and 15.5 miles of inland stream habitat.

What types of runoff treatment and erosion control techniques have been used in the Tahoe basin?

Best Management Practices (BMPs) are techniques for protecting or improving water quality. These can include BMP installation on new projects or BMP retrofits. This latter group forms an important component of the restoration strategy. Certain BMPs are required by regulatory agencies as conditions for constructing new structures or for remodeling existing structures. Examples include infiltration requirements for runoff from impervious surfaces and requirements to vegetate bare areas with approved plants. Other BMPs are used on projects constructed by public agencies to mitigate impacts of past development. Examples include lining earthen ditches and gutters with concrete, rock, or vegetation, installing sediment traps and basins to remove sediment from runoff, and spreading runoff across natural or constructed wetlands to remove nutrients.

Most BMPs were developed based on physical principles and experience from other areas. There is a limited amount of monitoring data at Lake Tahoe that has been used to evaluate the effectiveness of BMPs. Agency staff and project designers make decisions daily concerning what projects to fund and how to design the improvements. These decision-makers need to know which measures are working or not working and why. If a measure is not working effectively, they need to know how to make it work better. The monitoring data that exists is not readily available to the decision-makers.

A large number of erosion control and other water quality improvement projects have been constructed in the Tahoe basin over the past 15 years. Much has been learned from the experience of designing and constructing these projects and from observing project performance in the field. This information has been used to improve the designs of subsequent projects. However, most of the information has been qualitative and based largely on occasional site inspections and observations. Quantitative research on BMP effectiveness, focused on the questions below, should yield valuable data both for enhancing the performance of existing projects and for improving the designs of future projects.

At the request of the California Department of Transportation (Caltrans), scientists conducted a literature that which identifies stormwater quality BMPs that could be implemented for highways in the Tahoe basin (Currier et al. 1998). Summaries included four BMP characteristics: engineering feasibility, pollutant removal efficiency, cost, and secondary environmental impacts. The document also notes characteristics of BMPs that are not well researched and prioritizes further areas of study. The literature for this review was obtained from a number of sources throughout California, including the Lahontan Regional Water Quality Control Board (LRWQCB), CTC, TRG, and TRPA. It was found that the LRWQCB maintained the largest collection of relevant material. BMP categories are organized on the basis of snow and ice control, source control, vegetated systems, infiltration and filtration, detention/sedimentation, and channel linings. Each is summarized below and focuses on those aspects directly related to sediment and nutrient loading to the lake via surface and ground water runoff. In the sections below, information from the University of California, Davis report is combined with written material from Steve Goldman of the CTC, which was presented to the Tahoe Water Quality Working Group for distribution at the Second Science Symposium held at Lake Tahoe on February 10 and 11, 1999.

Utilized BMP Techniques

Snow and Ice Control Management Practices—Four general categories were identified: substance application, mechanical removal, traffic control, and construction. The use of salt can have significant effects on roadside vegetation, which could affect erosion.

Sanding is an abrasive application and has been used for many years. The efficiency of sand is size dependent, with the best particle size between one and two millimeters. When traffic grinds this sand into smaller particles it can become suspended in urban runoff. The nutrient budget presented in this assessment reported on the large amount of phosphorus entering Lake Tahoe via direct runoff. Highway and road runoff, which includes road sand, may be an important contributor. Furthermore, if sand is ground sufficiently fine its delivery to Lake Tahoe could directly affect water clarity. In the Tahoe basin, Caltrans used 35,706, 22,649, 24,137, 21,044, 19,420, 14,840, 22,678 and 16,759 tons of sand per year from 1988/1989 to 1995/1996.

Source Control Management Practices—Source control management practices are intended to minimize contamination in runoff before it is discharged to receiving waters. According to Currier et al. (1998), erosion prevention techniques are most widely used and appear to be the most cost-effective for highway maintenance. Once established, erosion prevention techniques typically require less maintenance than other BMPs. (Detailed information on feasibility was not found for most erosion controls.) Source control management practices were divided into those that work and those that have significant limitations for use in the Tahoe basin. Based on the review, the authors do not recommend the following systems for highway stormwater management: catch basins (sand traps), soil/water separators, porous pavement, and swirl concentrators. The first two have maintenance problems that result in high costs, but the nutrient removal characteristics of catch basins will be of interest because of the number already in place at Lake Tahoe. Catch basins have limited removal efficiency; approximately 40 to 75 percent removal of TSS, 15 to 30 percent of nitrogen, and only two to six percent removal of phosphorus (Lager et al. 1977). Removal efficiency will diminish with inadequate maintenance or increasing flows. The most likely area for further research is erosion control methodologies. While the cost of erosion controls are well known, the actual efficiencies and impacts on water in the Tahoe basin are not known (Currier et al. 1998).

Variability of climate, hydrology, soil type, topography, and maintenance in the Tahoe basin make outside research only marginally applicable. Research and monitoring should focus on the following: contaminant and runoff loading before and after BMP implementation, preventative capacity of the BMP, removal efficiency for loading, and project longevity. The BMPs considered to show demonstrated promise in the Tahoe basin include catch basins (limited application), maintenance practices, road reclamation, curbs, gutters and roadside channel stabilization, retaining walls, slope stabilization, stormwater diversions, and vegetative erosion control.

Vegetated Systems and Constructed Wetlands Practices—Vegetated systems, including wetlands and riparian zones, are recognized for their contribution to soil development, aeration and stabilization, shoreline protection, water treatment, erosion protection, ground water recharge, and many other aspects that contribute to a health ecosystem. In the Tahoe basin, stream environment zones (SEZs), described as wetlands or riparian zones, are recognized to provide an effective mechanism for nutrient and sediment removal from stormwater, for reduced flood peaks, and for increased retention time of surface flow (Currier et al. 1998). As a result, basin agencies not only encourage but require control measures for preserving and restoring SEZs. About 75 percent of the wetlands in urban areas at Lake Tahoe have been destroyed or altered, and TRPA has a goal of restoring 1,100 acres of these wetlands. Because of the natural treatment ability of wetlands and TRPA's goal, a major strategy of erosion control and water quality projects is to use wetlands for water quality treatment. The report concludes that "vegetated systems are effective in nutrient and suspended sediment removal; however, it is difficult to estimate the effectiveness level because the hydrology of the systems is not well understood. This limitation makes it difficult to predict the removal processes, efficiencies, and the relative roles of surface flow and subsurface flow." Because spring snowmelt dominates the seasonal hydrology in the Tahoe basin, water residence times for many vegetative (and mechanical) treatments is relatively short; this reduces treatment efficiency. Nutrient removal is further retarded by cold water and soil temperatures during the spring. Reuter and Goldman (1989a, b) provide examples of how hydrology and water residence time were factored into estimates of a combined detention basin/wetland treatment system. Hydraulic loads were used in the calculation of N, P, and TSS removal from these two components as part of the Ski Run Water Quality Treatment Facility and the Tahoe City Urban Improvement Project. In both, urban flow first was routed through a detention basin then was discharged to a linear wetland. Total calculated nutrient removal from the Tahoe City project was projected at 37 percent for total-N and 30 percent for total-P.

Commonly applied vegetated systems as BMPs in the Tahoe basin include wetlands, wet ponds, and buffer zones/SEZ. Sufficient information is available to show a demonstrable promise for wetlands and buffer zones/SEZs. Including wet ponds, filter strips, and grass swales to this list rounds out the list of BMPs with potential promise for Caltrans facilities in the Tahoe basin (Currier et al. 1998). Wetland treatment systems involve spreading runoff across well-vegetated areas, such as meadows. Studies have shown that wetlands are highly effective at removing sediment and nutrients from runoff. Most of the studies have been conducted outside of the Lake Tahoe basin. The literature suggests that a five-day residence time in a wetland is needed for maximum nutrient removal. Little or no conclusive data exists on nutrient removal in high elevation conditions or by season (such as when plants are dormant). As mentioned continuously throughout this section, research and monitoring on effectiveness of these systems is largely lacking.

Infiltration Management Practices—Infiltration practices remove sediment and nutrients as stormwater percolates into underlying subsoil. Infiltration structures often are termed retention basins. There are four general categories of infiltration practices: infiltration trenches, infiltration basins, exfiltration trenches (infiltration trenches with perforated pipe underdrains), and drainage/dry wells (Currier et al. 1998). The drainage area for infiltration trenches should not exceed five acres, and the site slope should not exceed five percent. The depth from trench bottom to the water table is three to 10 feet. A typical infiltration trench has a length to width ratio of at least 5:1, with a retention time of 48 to 72 hours to optimize removal efficiencies. Infiltration basins impound incoming stormwater until it percolates through the basin floor. Depending on the percolation rates, these basins are applicable for catchment areas between one to 12 acres.

The LRWQCB and TRPA require that runoff from impervious surfaces be infiltrated on-site. The standard is 100 percent retention of the 20-year, one-hour storm (one inch of rain in one hour at Lake Tahoe). This requirement is based on the fact that a forested watershed has little surface runoff (less than one percent of precipitation). In an undisturbed forest, nearly all rain and snowmelt travels to streams, lakes, or the ground water through the soil (i.e., very slowly and not on the surface). When land is paved, compacted, or covered with buildings, more than 90 percent of the precipitation runs off. Because this runoff occurs rapidly, in high volumes, and on the surface, erosion potential downslope in the watershed is greatly increased. Of greatest concern, high runoff rates change streamflow patterns, which may destabilize channel banks or cause channel bed incision in the lower watershed. Once started, this channel adjustment process can continue for many years. The infiltration requirements are intended to maintain or restore the natural hydrologic pattern.

Infiltration systems are required for new developments or remodels (residential and commercial) and for public improvements. At present, only a small percentage of Tahoe basin development, public and private, has been retrofitted to this standard. Eventually, all development in the basin may be required to be retrofitted. Infiltration systems on both private and public lands need to be monitored to determine how effectively they are performing and whether the performance declines over time. Data on effectiveness of infiltration in the Tahoe basin are limited; indeed, additional research is needed to determine the performance of these BMPs in cold-climates nationwide. If used in the Tahoe basin in conjunction with highway runoff, pretreatment measures to remove road sand would be needed.

Additional research and monitoring is critically needed. On erosion control projects at present, the agencies require only the portion of the road right-of-way within the project area to infiltrate. Sediment basins typically are sized to retain the runoff from the right-of-way area only, although basins often receive runoff from private lands and from national forests or other public lands. Private portions of the watershed are assumed to be retrofitted with infiltration systems at a later date. The effects of these additional runoff sources on basin performance is not known; however, basin trap efficiency is closely related to basin inflow rates. If a basin receives more runoff than it can store, overflows will occur. The overflows may contain high concentrations of fine sediment because the trap efficiencies for small particles are likely to be low (see discussion under sediment basins). In addition, high flows cause turbulence and resuspension of particles that were trapped during smaller storms. Currier et al. (1998) concluded that of all the potential infiltration techniques, only the infiltration trenches and basins are commonly used at Tahoe with demonstrated promise, and this technique could be used for highway facilities.

Detention/Sedimentation Management Practices—Detention is the short-term storage of stormwater to reduce flooding and to improve water quality. Sedimentation is the process whereby particles settle out of the water and onto the bottom. Aquatic vegetation and bacteria in these ponds also act to remove soluble nutrients via biological uptake. Detention basins also are referred to as wet ponds. The two general categories of detention basins are wet detention ponds and dry detention ponds (Currier et al. 1998). Wet ponds have a permanent pool and a storage volume that receives runoff, detains it, then releases it at a known rate. Extended detention allows for maximum pollutant removal. Dry detention ponds are dry between storms and are designed to hold peak design flows.

The trapping efficiency of a sediment basin is a function of each of the following key factors:

- Particle size of sediment;
- Basin surface area relative to inflow rate;
- Inlet-to-outlet relationship;
- Length-to-width relationship;
- Length-to-depth relationship; and
- Vegetative cover in basin.

Most basins seem to be effective at trapping large particles (sands and gravels). Small basins generally are ineffective at trapping fine particles (silts and clays). Most basins that are constructed are small relative to the volume of inflows; i.e., they are too small to trap fine sediment. Nutrients are believed to be associated with smaller particles. In any case, small particles, particularly clay-sized particles, stay in suspension for long periods, making them available for discharge to the lake. Basins that trap only coarse particles therefore, may be ineffective at trapping much of the nutrient load in runoff. Small basins may trap a high percentage of the sediment load in small storms, only to lose it during large storms when sediment becomes resuspended by high flows. Vegetation may reduce the degree of resuspension. Sediment basins are sometimes intended to serve the dual purposes of runoff infiltration and sediment trapping (see discussion under Infiltration Systems). While basins can perform both functions, they may be ineffective at one or both of them unless properly designed. For example, sizing a basin based on storing the runoff volume for a 20-year, one-hour storm may not provide enough surface area for trapping fine sediment, since basin surface area rather than volume is critical for sediment trapping. Secondly, sediment that settles in a basin bottom may reduce infiltration rates.

Fenske (1990) provided a number of examples of wet pond application in the Tahoe basin that included a review of many erosion control practices at Lake Tahoe. The High Sierra Pond and Harvey's Pond on the southeastern Nevada side of the basin were constructed in 1982 and 1983, respectively. Both are two to three acres in size and both have had problems related to high ground water levels resulting from project drainage. Bank erosion problems result from a lack of established vegetation around the High Sierra Pond; abundant vegetation around Harvey's Pond enhances nutrient uptake. Other examples of applications in the Tahoe basin include the Douglas County Dump

Restoration Project (1986), the Lower Kingsbury basin (1985), Tahoma Sediment basin (1988), and Granlibakken Sediment basin. For the Tahoe area, Fenske (1990) reported removal efficiencies of 70 percent for TSS, 35 percent for TP, and 30 percent for TN.

Most sedimentation/detention projects in the Tahoe basin have not been continuously monitored since their inception. This type of limited long-term BMP monitoring precludes understanding of how these BMPs operate at Lake Tahoe. Both monitoring and maintenance are necessary to analyze performance within the framework of adaptive management. Wet detention ponds, extended dry detention ponds, multiple pond systems, sedimentation traps and sedimentation basins all show promise in the Tahoe basin. However, as commonly observed, more information is needed regarding optimal design for the Tahoe basin, effectiveness, and maintenance requirements.

Channel Linings

There are about 435 miles of city and county roads on the California side of the Tahoe basin. In Nevada, there are county roads, state highways, national forest roads, and private roads. Most of these roads have unprotected drainage ditches along or below them. In the past 15 years, more than 100 miles of roadside drainage and channel improvements have been constructed or funded. Most of these improvements consist of asphalt or concrete curbs and gutters, culverts, and rock-lined or vegetated ditches. Curbs and gutters prevent erosion along road shoulders but do not provide water quality treatment. Because water flowing in paved gutters and culverts speeds up and cannot percolate into the ground, increased erosion potential often exists downstream of these hard structures. Rock and vegetative linings are intended to slow water velocities, prevent erosion, and allow some infiltration. Lined channels can be scoured if not properly designed or installed. Rock-lined ditches sometimes have been designed to also serve as infiltration systems. On some projects, a deep section of rock has been specified for this purpose. It is generally believed that infiltration is minimal on steeper slopes and during high flows. There is little data on the performance of channel improvements.

Review of Selected Case Studies from the Tahoe Basin

This section does not attempt to review all the restoration, BMP, or management projects that have been conducted in the Tahoe basin. Many projects do not have associated monitoring/evaluation reports, and those that do are too numerous to include here; consequently, selected examples are presented.

The Lake Tahoe Basin Management Unit of the USDA Forest Service has produced an extensive series of water quality monitoring reports that evaluate specific restoration projects, BMPs, and other management implementation. The goal here is not to review all these documents but to highlight the findings of a selected few with emphasis on common observations, sampling/monitoring design, and conclusions.

South Zephyr Creek Water Quality Report

Between 1987 and 1989, the Zephyr Cove Resort underwent extensive BMP retrofit work under the Federal Facilities Compliance Program (Lowry et al. 1994). This work included redesigning and paving parking lot parcels, installing curb and gutter, restoring a one-acre parking lot to a meadow, and installing 1,200 feet of infiltration trench. In total, the project was intended to prevent highly erosive overland flow on exposed soil with subsequent transport to the stream. The impact of a horse stable operation near the stream also was evaluated during the monitoring. Each of four stations was sampled 10 to 15 times each year. During base-flow periods, sampling was monthly but increased to weekly during spring runoff. Only mean annual discharge and suspended sediment concentration showed a significant decreasing trend using the data available for 1985, 1988, 1989, 1990, and 1991. However, Lowry et al. (1994) point out that because parameters such as suspended sediment and total-P are associated with flow, making comparisons among the various water years is difficult; that is, drought conditions may have been the cause for the reduction in suspended sediment. The authors discussed the possibility that the magnitude of improvement in water quality easily could have been masked by the even larger effect of the natural variation of precipitation and runoff on suspended sediment and other water quality constituents.

Water quality monitoring was also done in association with storms, when possible, and six such events were sampled between 1985 and 1990. In general, nutrient values did not increase dramatically over background levels during these events; however, an exception was a storm on August 18, 1985, when total-P was found to be 0.433 mg/L, or 24 times greater than the annual mean.

Griff Creek Erosion Control Project

Griff Creek was monitored in each of the nine years between 1985 and 1993. According to Lowry and Norman (1995), this monitoring was done to determine the effects of an erosion control project completed in 1984 designed to reduce erosion and sediment/nutrient loading to Griff Creek. This work was done as part of an effort to restore the original lower Griff Creek channel. Specifically, the objectives of the monitoring study were to determine if an in-stream sediment reduction basin could be effective in reducing concentrations of suspended sediment and nutrients in the creek and to determine the success of the streamside revegetation. These authors reported that the Griff Creek sediment retention basin was of limited use in long-term retention of sediment." The water quality monitoring data indicated that only during the first two years of operation did the retention basin reduce stream sediment. The maximum difference in flow-weighted annual mean concentration was 7 mg/L in 1986. After that time, there was no significant difference in suspended sediment above and below the basin, with only about a 2 mg/L difference. It was concluded that sediment retained in the basin during certain times of the year most likely was transported downstream as bedload during relatively high flows. As a result, downstream concentrations could exceed inflow concentrations as this material was flushed from the basin. Lowry and Norman noted that sediment trapped in the basin provides for less slowing of streamflow and therefore less trapping efficiency. Also, this BMP did not significantly reduce sediment during storms. A slight decline (not statistically significant) in nutrients was observed below the basin, which Lowry and Norman attributed to uptake by algae and other vegetation within and alongside the basin.

Vegetation colonization and growth along the stream and in the basin were very successful. The amount of vegetation in 1993 was reported to appear adequate to insure streambank stability during various flow conditions. The riparian species of willow and alder were particularly abundant.

Watson Creek Salvage Timber Sale

The Watson Creek, Carnelian Bay Creek, and Carnelian Canyon Creek watersheds were extensively logged between 1860 and the late 1960s. The most recent harvest activity, the Watson Creek Salvage Timber Sale, was implemented in 1990. The sale included 1,505 acres within these three watersheds. Approximately a third of the stand in the harvest or treated area was removed in a sanitation salvage operation. According to the LTBMU report, this operation included harvesting trees considered to be dead or dying and thinning overstocked stands. The operation was conducted by standard tractor logging techniques. Water quality monitoring was primarily limited to the Watson Creek watershed despite the fact that only five percent, or 80 acres, in the entire watershed was treated. This was largely because the intermittent nature of the flow in the drainage of the other two watersheds, which were more heavily treated (41 to 56 percent), prohibited an adequate upstream versus downstream sampling design. Samples were taken in 1990 (considered a preharvest year) and in the four subsequent years, 1991 to 1994.

Norman (1996c) concluded that "the results of this analysis indicates that timber sale activity appears to have had negligible effects on water quality." The application of this finding to other timber sale parcels was not discussed. Increases in nitrogen were observed in Watson Creek below the sale site, but this was observed in the 1990 pretreatment data set. The variability of the data was such that it was difficult to statistically detect upstream versus downstream differences; however, based on the available database there did not appear to be a large or consistent effect in sediment or nutrient levels. The report concludes by stating that further monitoring is needed to better understand the effect of timber harvest activities on sediment and nutrient loading to tributaries.

Wasiu I and Wasiu II Timber Sale

This report evaluated the impacts of the Wasiu I and II timber sales on the water quality of Meeks Creek (Norman 1997b). These sales were implemented between 1989 and 1995. The purpose of this harvesting was to remove stands of mistletoe-infected lodgepole and decadent Jeffrey pine and white fir from the Meeks Creek meadow. Thirty to 100 percent of the stand within the harvest area was removed in a manner similar to that described above for the Watson Creek project. A hundred and sixty-four acres were harvested, which represents 13.7 percent of the nearly 1,200 acres in the subwatershed between the two monitoring stations.

The USDA Forest Service began monitoring the water of Meeks Creek in 1980. This provides an extensive preharvest database, something that is lacking in many of the BMP-type restoration projects in most watersheds nationwide. For the purpose of their analysis, LTBMU scientists considered the 1980 to 1986 database to represent pretreatment conditions and the 1990 to 1994 database to characterize conditions during harvest. Post-harvest was interrupted by a 100-acre burn in the project area in the fall of 1995.

Nonparametric statistics were used to determine if statistically significant changes in water quality were observed between the before and after timber sale data. These tests examine the differences in the median rather than the mean data points and are used when data is not normally distributed or when it cannot be appropriately transformed. The following conclusions appeared in this report:

- Suspended sediment did not increase during the sale years except in 1992. The raw data showed that during three weekly samplings in the spring, suspended sediment concentrations were much higher at the downstream site.
- The difference between the below versus the above harvest sites for turbidity increased from 0.0 Nephelometric Turbidity Units (NTU) before the sale to 0.085 NTU after the sale. This was significant at the 95 percent confidence level.
- Concentrations of nitrate were consistently higher at the upper site before and during the timber sale; however, the decrease between above and below was significantly reduced during the sale. Because harvesting was to the edge of Meeks Creek and most of the removed trees in this area were live, this decease in nitrate reduction could have been due to less biological uptake by riparian vegetation (Norman 1997b).
- Neither dissolved or total phosphorus increased during the timber sale.

The report clearly states that this analysis should not be the final word on the impacts of timber harvesting on water quality; however, the results are encouraging in that they do not show a major change. These conclusions are significant in that they are based on a robust, long-term data set. Norman recommends continued monitoring at future timber sales, whenever the following criteria can be met: above and below sites can be established on perennial streams, and a significant portion (25 percent) of the subwatershed between these two sites will be harvested, and at least three years of preproject data can be obtained. These criteria require careful planning of not only the monitoring programs but of the restoration and implementation activities.

An update of this study, which presents the results of monitoring through 1998, is being peer reviewed but will be available through the USDA Forest Service (Widegren 1999).

Pope Marsh Burn

Water and soil quality in Pope Marsh was monitored from 1995 to 1997 to evaluate the impacts of an 11-acre low-intensity controlled burn in September of 1995. The water quality monitoring was to determine concentrations and duration of nitrogen and phosphorus release to surface waters resulting from this burn.

Soil was monitored for nitrogen content

prior to snowfall in 1995, 1996, and 1997 (the 1995 sample was after the controlled burn) (Norman and Widegren 1998). Water quality samples were collected during the spring runoff period at three sites: upstream, below Highway 89, at the Tallac Lagoon inlet, and at the outlet of Pope Marsh below the burn site. According to Norman and Widegren (1998), soil chemistry indicated that ammonium-N concentrations increased by almost 15 times over background in the first year after the burn. Nitrate-N doubled two years after the burn. Both these soluble forms of nitrogen returned to background concentrations the following year.

Comparisons of spring runoff data from 1995 and 1996 did not exhibit a noticeable change in water quality associated with the burn; however, the authors did caution that this is a limited database and that more sampling is required. The report stated that "spring runoff data does indicate that sediment and turbidity levels decrease from the Highway 89 inlet to the outlet of Pope Marsh, whereas nutrient concentrations are consistently higher at the outlet, regardless of the effects of the burn." In general the results led Norman and Widegren (1998) to speculate that this portion of Pope Marsh may have exceeded its ability to filter nutrients. They noted that if this is true it could be due to the flow regime and urban influences on incoming nutrient levels; however, more specific analysis is desirable.

One-day intensive sampling at multiple sites indicated that in 1996 and 1997 nitrogen concentrations, as nitrate and TKN, were nearly double below the burn, compared to above the burn. In 1996 the USFS reported that concentrations fell to above burn levels at the marsh outlet, while in 1997 concentrations at the outlet were similar to those below the burn. It was unclear why nitrogen at the marsh outlet increased between 1996 and 1997; Norman and Widegren (1998) suggest it was due in some manner to the fact that the marsh outlet was blocked for almost all of 1997. Regardless, this work indicates that in Pope Marsh this burn many have contributed to nitrogen mobilization and transport. The authors acknowledge that this data set is too limited to yield unambiguous conclusions.

Douglas County Department of Public Works

In 1982, a number of erosion control structures were placed along Nevada State Highway 207 (Kingsbury Grade) to reduce sediment and nutrient transport to Edgewood Creek. Structures consisted of rock gabions, wooden retaining walls, rock lining on roadside ditches, curb and gutters and vegetative slope stabilization. Sediment retention basins were also built. The effect of this work on sediment and nutrient transport was monitored (Garcia 1988). Before construction and after construction monitoring lasted for approximately 12 months each.

Three sites in the Edgewood Creek watershed were used to examine the efficiency of erosion control structures (Garcia 1988). The first site was located in a relatively undisturbed area. Although there was one urban area, runoff first passed through a meadow before reaching the stream. The second site received urban runoff, and had several erosion control structures consisting of rock gabions (cages), retaining walls, rock linings of roadside ditches, curbs, gutters, and slope vegetation located throughout to control runoff from State Highway 207. Site 3 was downstream and received the total streamflow from sites 1 and 2. The stream water was studied between 1981 and 1983 and was tested for velocity, total sediment, total N, total P, and total iron. The erosion control structures were built in 1982, so it was possible to compare the streamflow characteristics before and after implementation. Site 1, the control, contained more sediment, which may have been the result of increased precipitation that year. At site 2, sediment concentrations were reduced significantly, from 24,000 to 410 mg/L. This is particularly significant because stream discharge increased due to greater precipitation. The sediment load at Site 3 also was reduced by a factor of about 10. Nitrogen concentrations did not change much at any site as a result of erosion control. Total P was unchanged at Site 1 but was significantly reduced at Site 2, presumably because of the reduction in sediment discharge. Despite the decrease in sediment discharge, the total P concentration actually increased at Site 3. The reason is unclear, but it is possible that finer sediments that are more likely to contain mineral complexed-P were not retained.

California Tahoe Conservancy

The following examples are case studies of projects that have been constructed in the Tahoe basin, as written by Steve Goldman of the CTC. They also illustrate some typical problems and conditions and explain what kinds of monitoring are needed and why. The focus of these examples is wetland treatment, because this approach is a key element of the water quality improvement strategy for the basin.

Ski Run, Tahoe City, and Stateline Water Quality Improvement Projects

Key features of these projects include a centralized treatment approach with a two-stage system of constructed wetlands. A major water quality control strategy in the Tahoe basin is to collect and treat runoff from large urban areas in a centralized treatment facility, which uses constructed wetlands. This approach is generally used in association with community redevelopment projects. However, these larger centralized projects cannot necessarily be done to the exclusion of individual treatment BMPs on private parcels when they are needed. Three multimillion dollar projects recently have been constructed, which employ a two-stage treatment system for urban runoff (a 175-acre developed area between Highway 50 and Pioneer Trail near Wildwood Avenue in South Lake Tahoe, the Stateline area just west of Park Avenue and below Highway 50 in South Lake Tahoe, and the Tahoe City urban area above Highway 28 west of Grove Street). The first stage is a large basin designed to hold the runoff of a 20-year, one-hour storm from the surrounding area. The second stage is a constructed wetland designed to receive a controlled flow from the basin, thereby to remove sediment and nutrients. The concept is to collect and store the runoff so that it can be treated slowly over time because it is believed that high rates of nutrient removal will be achieved with trickling flows through wetlands.

The above projects were designed with controllable inlets and outlets and bypass systems, so that flows through wetlands can be adjusted. It is important to implement effective, long-term monitoring programs for these projects to determine how effective they are and to determine how they could be made more effective, particularly because this approach has a high construction cost and is being proposed to be implemented again on other sites. Monitoring program descriptions have been developed for each of these projects but have not yet been put in place. At the Tahoe City site, the basin and wetland have been constructed, but the drainage collection system to convey runoff from the urban area to the basin is expected to be completed within the next two to three years.

Pioneer Trail I Project

Key features of this project include enhanced meadow treatment as a moderate cost, one-stage treatment system. On many sites, existing wetlands or meadows provide opportunities to treat runoff. On the Pioneer Trail project, runoff from subdivisions along Pioneer Trail discharges into a disturbed meadow near the intersection of Highway 50 and Pioneer Trail in Meyers. The meadow was altered by human activities and had relatively poor vegetative cover at that time. The runoff had carved a ditch along the far side of the meadow. This project, which was constructed in 1989 and 1990, rerouted the runoff into the center of the meadow. Willow brush fences, willow wattling, and rock check dams were constructed to cause the water to spread laterally across the meadow.

This project was monitored from 1989 to 1991 (Reuter et al. 1990; Reuter and Goldman 1992). Data from this site during the first winter after construction showed up to a 50 percent drop in runoff volumes from the upper to the lower end of the meadow. While the mean sediment concentration and load dropped by 30 to 40 percent between the inflow and outflow, nutrient concentrations did not change significantly. This lack of change may have been due in part to the low density of vegetation in the meadow at the time of construction. During the initial part of the monitoring period, a rise in suspended sediment concentrations between inflow and outflow was observed. When the site was inspected, runoff was found to be escaping from near the middle of the meadow back toward the ditch on the periphery. As water fell down the embankment into the ditch, scour was occurring, which explained the spike in sediment concentrations. After this short-circuiting was corrected, sediment concentrations in the meadow outflow returned to previous levels. This example illustrates the importance of evaluating BMP monitoring data, analyzing anomalies, and inspecting the site.

Monitoring at the Pioneer site ended after the first year due to a lack of funding. When the project was constructed and monitored, plant density on the treatment area was relatively sparse, with plants about three feet apart. In the nine years since construction, plant density throughout the meadow has increased substantially. Monitoring this site again would help to determine if the relationship between sediment and nutrient concentrations between the meadow inflow and outflow points has changed since the initial monitoring period. Because this is one of the oldest meadow treatment sites in the basin and was well monitored during the first year after construction, this monitoring would provide important information to validate the effectiveness of wetland treatment systems.

West Sierra Project

Features of this project include a small-scale wetland constructed in an excavated basin on a wet well-vegetated site, with a small surface area relative to inflow. The West Sierra basin is located along Sierra Boulevard at Chris Avenue in South Lake Tahoe. This basin receives runoff from Highway 50 and a portion of the Sierra Tract. It was constructed in 1989 and now contains a dense stand of sedges, rushes, and grasses in the basin bottom. Though this basin occupies three vacant lots, its surface area is small, relative to the inflow rate (i.e., residence times are not ideal for large storms). Because the basin is so well vegetated, it would be an excellent site to evaluate the ability of vegetation to enhance detention basin performance (e.g., by trapping fine sediment by mechanical filtering and preventing resuspension). If such basins are shown to be effective, they may offer an alternative to increasingly difficult land acquisitions needed to achieve design capacities.

Angora Project

The Angora project uses an existing meadow to treat runoff. Street runoff is routed into the meadow, and berms are used to spread flows. This project is being monitored by El Dorado County with a grant from the CTC. The USFS is assisting El Dorado County in monitoring the Angora project that began in 1998; the USFS began monitoring for an eventual upstream-downstream comparison in 1994.

What is the effect of large hydrologic events on BMP and restoration effectiveness?

Large hydrologic events, such as floods, present an obstacle to effective planning. Unfortunately, there is even less information available on the effects of extreme hydrologic events on BMPs than there is on general BMP effectiveness. There is no question that much more event-based data are needed to assist planners and decision-makers in setting their project priorities. Clearly, extreme events are beyond the design capacities of most BMP and restoration projects within the basin. They are important however, because such events disturb natural systems for long periods; hence, planners need to know and understand the hydrologic history of a subbasin before restoration goals can be adequately established. Evaluation teams are needed to assess damage to existing BMPs after large hydrologic events.

The Second Creek flood of 1967 produced approximately 75,000 tons of sediment in a single afternoon, which is more than the estimated combined annual average for First, Second, Wood, Third, and Incline Creeks (Glancy 1969). Often, current and historic land use and the effects of previous extreme events overlap. Glancy (1988) reported that the amount of available sediment in Second Creek increased after the flood but before stabilizing vegetation was reestablished. Landslides into the channel (but not out of the drainage) created a pool of available sediment with no vegetation to retard mobilization of the sediment after the mudflow. Sediment yield (tons/mi^2) was larger for Second Creek than all the others (Glancy 1988) for the entire study (1970 to 1973). However, four years is probably too short a period for adequate recovery from the flood and mudflow event.

Other more indirect sources of information can be derived from BMP monitoring over periods that have included storms of above-average intensity. For example one large event in Incline Creek was found to produce more sediment and nutrient discharge than all other summer events combined in 1996 (Sullivan et al. 1998). Another documented example is the Apache Erosion Control Project (Robinson 1996). With five years of monitoring (WY 1991 to WY 1995), there were enough hydrologic events to separate normal rainfall from violent thunderstorms. The latter were found to result in tributary nutrient and sediment discharge concentrations that exceeded rainstorms by factors of 2 to 30. This significant departure from a typical average annual scenario indicates the potential for extreme thunderstorms such as that of the Second Creek flood to negate BMP and restoration project effectiveness.

Can the expected reduction in sediment and nutrient loading to Lake Tahoe assuming varying restoration and implementation scenarios be quantified?

Restoration activities monitoring has not been sufficient to quantify load reduction on a large-scale basis. The effectiveness of management strategies often depends on yearly precipitation and large storms. Time scale also is a factor. Erosion control structures in particular are expected to lose their effectiveness with time. For example, a well-monitored sediment retention basin on Griff Creek was found not to reduce sediment discharge after only two years of operation, nor was it effective during large storms (Lowry and Norman 1995). Unfortunately, sediment and nutrient loading is most severe during large storms when BMPs are generally not effective.

Adequate site-specific quantification of nutrient and sediment loading is problematic. Annual, seasonal, and even daily changes in tributary discharge make adequate measurement difficult to attain. Rates of vegetative growth and nutrient uptake, rain-on-snow events, soil conditions, and localized atmospheric deposition all are factors that enhance or reduce nutrient loading, and all are difficult if not impossible to predict. A loading reduction following channel stabilization in one particular watershed cannot be interpreted as being able to provide the same level of effectiveness in a different watershed.

Note that each watershed contains site-specific conditions that cause it to respond differently to given restoration activities. With proper monitoring and subsequent interpretation of data, however, it is possible to identify trends in the characteristic effectiveness of specific restoration projects. Sufficient monitoring over time on enough different sites throughout the basin, where the same or similar restoration activities have been implemented, can provide useful information on the potential for success or failure in a given situation. New and innovative techniques in particular need careful multiyear monitoring to allow for trend assessment. For instance, sediment loading may be reduced by 35 to 50 percent in the first year, but it then decreases about 10 to 15 percent in effectiveness each following year. Such reductions must take into account changes in streamflow and annual events. The effective lifetime of a sediment detention structure is a function of streamflow and precipitation. Trend analysis is then useful for predicting which restoration activities could be expected to exhibit a positive effect on nutrient and sediment load reduction and for how long.

Long-term BMP effectiveness monitoring is rare because it is very expensive. However, in the long run it would be much more cost-effective to determine how well BMPs work over time, before millions of dollars are invested in projects that may or may not meet their objectives (Sierra Nevada Ecosystem Project 1996).

How will prescribed burning affect sediment and nutrient reservoirs in the watershed and the system hydrology and ultimately the loading of these materials to Lake Tahoe?

The frequency and intensity of wildfires in the US has increased over the last two decades. Fire suppression efforts since European settlement may have delayed wildfires, but they cannot over the long term prevent them. Prior to 1900, low intensity burns characterized both ponderosa and Jeffrey pine sites, which had average fire return intervals of 2.5 to 15 and 14 to 18 years, respectively (Dietrich 1980). After the early 1900s, the introduction of domestic livestock and fire suppression led to the establishment of numerous new trees in these ecosystems. Dense stands of young trees, lacking recurrent fires, readily built up high levels of fuels such that present-day fires are often catastrophic, killing virtually all trees in the fire zone (Mueggler 1976; Peet 1987).

Statistics on wildfire extent indicate a bimodal distribution reflecting first fire suppression between 1916 and the 1950s, when wildfire extent decreased from 0.4 to 1.5 million ha/yr to <0.3 million ha/yr, followed by an increase to approximately pre-1930s levels in the 1980s and early 1990s (Arno 1996). The latter increases are attributed to a combination of woody understory fuel buildup due to past fire suppression and to drought and insect attacks. If projections for drier and warmer climates in the southwestern US hold true, the extent and frequency of wildfires can be expected to increase in the future.

From a public safety perspective, the threat of catastrophic wildfire in semiarid ecosystems has increased dramatically over the last few decades, due to past fire suppression and consequent fuel buildups, a danger that may be exacerbated by climatic change. Revegetation of areas burned by wildfire presents significant problems for land managers. Furthermore, biogeochemical cycling in semiarid forest ecosystems will require shifting from solution fluxes, which dominate inputs and outputs in humid forests, to the more episodic flux of gaseous exports and N_2 fixation inputs, which tend to dominate fire-structured ecosystems. Prescribed fire almost certainly will be required to reduce the threat of wildfires.

As urban populations grow, they expand into forests and rangelands, and concern grows about the fire danger near the urban/wildland interface. Hence, forest managers are becoming increasingly concerned about higher fuel loads and fire hazard adjacent to areas of development. The use of prescribed fire as a management tool for reducing fuel and improving forest health is appealing. Public perception and understanding of prescribed burning, however, can limit its applicability. Overall assessment of prescribed fire as an effective BMP in the Tahoe basin cannot be adequately evaluated without a more complete understanding of the processes in their social and ecological context. Knowledge of the probable long-term results of prescribed fire for plant communities and the kinds of burning and revegetation techniques that will best achieve desired forest, rangeland, and environmental conditions is also needed. Understanding of vegetation dynamics, requires additional knowledge of how fire or a burning program affects nutrient storage and movement through the ecosystem; that is, the functional processes that underlie forest and rangeland conditions. Burning affects infiltration rates, nutrient content, and nutrient cycling.

Approximately 25 to 49 percent of standing trees in the Tahoe basin are dead or dying (Sierra Nevada Ecosystem Project 1996). Dead or dying trees are easy targets for disease and insect infestation and catastrophic wildfires. There are two forest fire scenarios. On the one hand, a high intensity wildfire would destroy all vegetation, filling the basin with smoke and potentially creating conditions conducive to excessive sediment and nutrient loading. On the other hand, a low intensity fire generally occurs over a smaller surface area with less heat. The duff layer remains intact, and soil water repellency following a low intensity burn reportedly has been minimal (Norman 1997a). The potential for site erosion following a fire depends on the initial erodibility of the soil, slope, precipitation characteristics, severity of fire, development of soil water repellency, and plant cover remaining following the burn (Pritchett and Fisher 1987). If a fire does not consume the entire surface organic horizon, the effects on infiltration and pore space are generally minimal. Hence, runoff, erosion, and sediment and nutrient transport presumably would be lessened. Through prescribed burning, the forest would seemingly reap the benefits of fire without having to endure the adverse ecological impacts of a catastrophic high intensity wildfire. An average of 500 acres per year have been burned by prescription in the past 10 years. Prescribed burns have taken place in Incline Village and on the southwest side of the lake (Rowntree 1998).

Effects on Nutrient Cycling and Transport

Post-fire revegetation is a severe problem in many cases. *Ceanothus velutinus* is a pioneer species that invades after site such disturbances as fire in the eastern Sierran forests. *Ceanothus* is especially adapted to fire; heat treatment followed by cold stratification is required for seed germination (Zavitkovski and Newton 1968; Youngberg and Wollum 1976). Seeds lying dormant in forest litter for many years are activated by fire and winter weather, resulting in prolific germination in areas of wildfire, clearcut, or slash burn. *Ceanothus* is shade-intolerant and therefore disappears with overstory canopy closure; however, *Ceanothus* presents serious competition for forest regeneration after fire, when it is not controlled by other means. For example, *Ceanothus* completely dominates areas of the former Donner Ridge fire (1960) near Truckee, California. Forest regeneration is virtually absent. On the other hand, in Little Valley, Nevada, patches of *Ceanothus* are common in a mosaic of 110-year-old Jeffrey pine forests. Furthermore, the benefits of *Ceanothus* on site fertility are clear; it replaces the N lost in fire and usually results in greater soil carbon and N contents than were there originally (Youngberg and Wollum 1976; Binkley et al. 1982; Johnson 1995). A prescribed low intensity burn in Pope Marsh resulted in increased nitrogen loading in spring runoff prior to the reestablishment of vegetation on the site (Norman 1997a). Monitoring was not continued following revegetation, but available nitrogen would be expected to decrease with enhanced plant uptake. The long-term effects of low intensity prescribed burning is under investigation (Miller and Johnson, unpublished).

The long-term deterioration of water quality in Lake Tahoe has been clearly documented, with a possible shift from N limitation to one of N and P co-limitation or P limitation over the last few decades as N inputs to the Lake have increased (Goldman et al. 1993). This deterioration is thought to be due to increasing nutrient loading from development, atmospheric deposition, and possibly N-fixation by riparian mountain alder (Coats et al. 1976; Leonard et al. 1979; Byron and Goldman 1989). Thus, the effects of fire (wild or prescribed) on N and P transport to the lake are of considerable concern. One study thus far has reported that P concentration in runoff was the same from an unburned forest as from an area where prescribed burning had taken place (Rowntree 1998). Rowntree (1998) also found that nutrient availability was affected by other factors after a burn, such as calcium, which formed a Ca-P complex that would be biologically unavailable for algal uptake.

Fire also can have a longer-range and more indirect effect on Lake Tahoe because of dry deposition of particulates from smoke (Goldman et al. 1990). Although smoke has been observed to increase algal blooms (Goldman et al. 1990), why this occurs is unclear. Studies that address the specific composition of forest fire smoke are needed. It may be that different varieties of trees produce different constituents in the smoke, or that burning at different times of the year would have dissimilar effects. This may be especially true for nitrogen, which is held in the vegetation and soil in greater amounts at different times of the year (Rowntree 1998). Nitrogen is volatilized at temperatures exceeding 200 °C (White et al. 1973), and 85 percent of the soil organic matter is lost at temperatures between 200 °C and 300 °C. Prescribed fires, however, usually remove less than half of the surface organic layers (Pritchett and Fisher 1987). These immediate losses in N can be regained as the site is re-vegetated. Nitrogen-fixing vegetation such as *Ceanothus* thrives on burn sites but can serve as a source of excess leachable N (Johnson 1995).

Are the available data from demonstration projects and other monitoring activities in the basin adequate for management decisions at the watershed scale? What are the concerns associated with managing restoration at both the project and watershed scales?

For environmental sustainability and restoration practices to be most effective, the efficacy of available BMPs should be known before they are implemented. Unfortunately, complete monitoring data for BMP application in the Tahoe basin are largely lacking. Previous site-specific activities provide a starting point for generating a BMP effectiveness database, but efforts to incorporate BMP analysis at the watershed level are just beginning.

Sources for currently available data are varied. The USFS has produced a number of project reports that include project monitoring information, as previously described. The private sector often produces similar reports, although these are not as readily available to planners/managers who were not associated with the original project effort. The LTIMP program routinely collects and distributes surface and subsurface water quantity and quality data for Lake Tahoe. While these data are generated basin-wide, they are intended to measure nutrient and sediment loading in some of the basin's major tributaries and not to evaluate BMP effectiveness. The TRPA also collects and reports water quality data relative to established environmental threshold values (Hill 1994); but again, these data are not necessarily related to BMP evaluation.

The types of BMP demonstration projects studied to date are varied and include erosion control (Hoffman 1991; Robinson 1996), ground water (Duell 1987), timber sales (Norman 1996b), an analysis of land use and tributary water quality (Byron and Goldman 1989), and stream restoration (HydroScience 1997; Inter-Fluve and Services 1996). These individual studies can provide some useful information to planners and managers about effective sampling design and site-specific concerns but do not allow for techniques to be implemented basin-wide with high certainty of success. Even monitoring efforts with similar goals (e.g., erosion control effectiveness) can be incomparable if different techniques or measurements are employed. Basin-wide integration, or even effective integration over a single sub-basin, has yet to be proven successful.

To facilitate comparison among the various demonstration and monitoring projects, only those reports prepared by the same agency were evaluated. Thus, issues of different field and data analysis techniques can be largely avoided.

The USFS has conducted several monitoring projects related to BMP effectiveness (Hoffman 1990, 1991, 1986; Norman 1996a, 1996b. 1996c, 1997a, 1997b). While it appears that many erosion control projects have been somewhat effective in reducing sediment loads, some have been unsuccessful. For example, several projects on Blackwood Creek failed to reduce either sediment or nutrient loading. Undiminished levels of sediment and nutrients were attributed, in part, to historical activities (Lowry et al. 1994). However, there is also evidence that the reduction of sediment load is short-lived. A sediment retention basin in the Griff Creek basin was found to reduce sediment load over a two-year period, after which the sediment leaving the structure was equal to that entering (Lowry and Norman 1995). Furthermore, erosion control projects have provided little evidence supporting a consistent trend with regard to nutrient loading. Indeed, Robinson (1996) provides data illustrating considerable variability in nutrient loads downstream from erosion control projects.

Data from another management practice, controlled burning, have demonstrated increased nitrogen discharge from burn sites immediately following burning (Norman 1997a). The increase in loading continued until vegetation had reestablished. Although this was a short-term and controllable process (BMP), the effect must be explicitly considered when evaluating total nutrient loading to adjacent tributaries and the Lake itself.

Establishing SEZs is another BMP currently applied within the Tahoe basin. While there are other well-established benefits, SEZs can exhibit a major effect on nutrient transport processes. Restored floodplains allow suspended sediment to settle out of suspension before entering the lake and can reduce total sediment and nutrient load. Several specific projects (HydroScience 1997; Inter-Fluve and Services 1996) also have been successful in creating long-term habitat stability. However, the effectiveness in terms of nutrient loading is unknown. The geomorphic properties of natural SEZs are developed over time and are influenced by watershed level, if not basin-wide ecosystem interaction. Attempts at channel restoration, without a clear understanding of how the total ecosystem interacts, ultimately may result in project failure and be expensive to both the environment and the economy. Because there is no existing presettlement database from which to work, projects that seek to restore channel morphology to presettlement status are certainly problematic. SEZ projects, more than others, must be considered at the watershed level of cause/effect interaction.

The most significant finding from a review of the literature is that none of the projects effectively reduced existing loads to below TRPA threshold level specifications. When stream water quality was above the specified threshold prior to project implementation, it remained so even when the project was effective in reducing total sediment and/or nutrient loading. In addition to site-specific evaluation, BMP effectiveness also should be evaluated at the watershed scale. This is clearly the case for fluvial processes. It is possible that sediment loading to the lake may be reduced by projects implemented outside the actual areas of proposed disturbance. When TRPA thresholds are exceeded upstream of developed areas, control projects have to mitigate local disturbance and the natural or background upstream water quality. Only combined scale assessment (including land use history) will ultimately determine what levels of BMP effectiveness are truly possible.

The 63 watersheds within the Tahoe basin are subject to different stages of land development and contain different geomorphology, soils, precipitation, and vegetation. Such diverse areas may behave quite differently when disturbed or restored. To be most successful, restoration needs to be tailored to specific watershed conditions.

Because there are so many variables affecting watershed sensitivity, different watersheds may need to be managed separately. As part of the Forest Service's Watershed Improvement Plan Series, each watershed under examination was examined to provide information on soils, vegetation, land use, channel stability, erosion hazards, and water quality. Suggestions for channel restoration, erosion abatement, and land use management were included. Updates of this program are essential to identify what kinds of problems are most easily addressed. Once a workable solution is found for a given type of problem, it may or may not be feasible to use it basin-wide. The more that is known about a specific watershed, the more feasible it will be to restore it into its previous or desired condition. Comprehensive monitoring of the effects of restoration in any given watershed is a critical step before restoration is attempted elsewhere in the basin.

The aforementioned issues of watershed variability not withstanding, there might be real value in establishing one or more demonstration watersheds. These demonstration watersheds could serve as models for how to, or how not to, design, implement, and monitor BMPs to achieve positive results at the watershed scale. While specific results might still vary among watersheds, the process of designing, implementing, and monitoring would be more robust.

What are the primary characteristics of a potential project that should be used to rank its priority (e.g., distance from the lake, proximity to roadway, land slope, soil erodibility, and hydrologic connectedness to other disturbed areas)?

The highest priority projects should be those that will have the most significant beneficial impact on discharge water quality and, consequently, lake clarity. The role of the Lake Clarity Model, in development, is significant in this regard. Relatively easy cheap projects include revegetation, trail maintenance, and channel stabilization. If done properly, these projects have a good chance of immediately reducing sediment and nutrient transport and deposition. Erosion control projects are generally high priority for reducing sediment transport and discharging particulate P sources. Sources of accelerated erosion within a watershed are usually apparent. System roads often have gullies or spurs from excessive erosion. The LTBMU's Watershed Improvement Plans provide a list of erosivity problems for each watershed. The most serious problems identified occurred on system roads, recreational trails, streambanks, and drainages and were due to off highway vehicle use. Projects near streams are important because stream zones are more likely to increase nutrient and sediment loading with disturbance. Restoration of wetlands is equally important because of the potential for both enhanced nutrient and sediment removal.

TRPA rates building suitability of residential parcels by the Individual Parcel Evaluation System (IPES). Sites with high scores are considered to have low impacts on watershed processes and therefore are suitable for development. In order of most to least critical, the classification evaluates erosion potential, runoff potential, ease of access, SEZ proximity, condition of watershed, revegetation ability, need for water quality improvements, and distance from lake. Disturbed parcels with very low scores should be a priority for remediation (Tahoe Regional Planning Agency 1999).

It is important to differentiate between feasible projects and those that are infeasible because of cost or inherent nature. For instance, Blackwood Creek has steep slopes with rock outcrops. These slopes would not be good candidates for revegetation, but the watershed might well benefit from measures to reduce the runoff velocity (USDA Forest Service 1989b). Erosion control projects at Blackwood Creek reportedly have been unsuccessful due to naturally high levels of sediment discharge from the adjacent slopes (Lowry et al. 1994). The target level for restoration should be based on what is reasonably expected and on the monitoring and evaluation of similar projects elsewhere. Restoration in the Tahoe basin should be focused on cost-effective simple solutions and should be based on the possibility that a severe hydrologic event could destroy constructed improvements.

Because the lake responds to nutrient or sediment loading regardless of the watershed of origination, those projects that have the shortest delivery time (time of transport) to Lake Tahoe should be the focus. As presented in the discussion of the nutrient budget, direct runoff from the urbanized areas around Lake Tahoe appear to be significant contributors of phosphorus. Projects located more upland in the watershed may generate pollutants that are trapped or otherwise removed as flow proceeds downslope. These would not be identified as priority projects. Projects that directly discharge to the lake or its tributaries should be attended to first.

In any new attempt to prioritize restoration projects in the basin, previous restoration efforts should not be ignored. For example, in 1986 the CTC entered into an agreement with the Tahoe Resource Conservation District (RCD) and the USDA Soil Conservation Service (now NRCS) to produce an evaluation report of 95 proposed projects (Sletten 1992). A similar approach was used to rank 22 projects in Nevada in 1988. Similarly, a priority list of erosion control projects was developed as part of the original 1978 TRPA 208 Plan and the 1980 State Water Resources Control Board Lake Tahoe Basin Water Quality Plan.

The evaluation scoring system proposed by Sletten and others ("Tahoe Basin Capital Improvement Program—Evaluation of Proposed Erosion Control Projects") considered six aspects: sediment reduction in terms of pounds per dollar, watershed condition (referenced from TRPA Code, IPES Program), public or private benefit, distance from SEZ, distance from project to Lake Tahoe, and average flow of major stream within project watershed. Sediment reduction was determined as the difference between calculated "before" and "after" erosion rates from each parcel. Before rates were obtained from the SCS Universal Soil Loss Equation, or the empirical estimate for concentration flow erosion (Sletten 1992). BMP effectiveness values were used to estimate the reduction in sediment loss.

As discussed elsewhere in this section, restoration activities should be considered on a number of levels, including effectiveness at the project scale (i.e., removal capacity) and the watershed scale (i.e., overall contribution of a project to reduce nutrient and sediment loading). It was beyond the scope of this document to assess whether individual projects in multiple watersheds is preferable to focusing a major restoration effort in a single watershed; to the extent that unpercolated flow from an upstream project increases erosion downstream, the latter may be more effective. This is an issue that must be addressed further in any consideration of project priority.

What are the implications for future monitoring?

Specific BMP effectiveness in the Tahoe basin is largely unknown due to the overall lack of comprehensive monitoring data and the absence of a thorough and well-integrated review and evaluation of all existing data. The aggregate effect of previously implemented BMPs is also unknown. It may be that the BMPs installed to date have not been as effective as hoped or more likely, that the number of implemented BMPs has not been sufficient to stem the magnitude of sediment and nutrient loading, in which case a much larger effort would be required. Given the estimates that nutrient retention times in Lake Tahoe are on the order of decades (Jassby et al. 1995), lake clarity responds not only to annual loading but to historical loading as well. This condition underscores the need for predictive modeling of lake response based on management scenarios.

BMP effectiveness can be studied over a much shorter time frame if there is a clear understanding of the various nutrient pools, how they cycle biologically, and the pathways by which nutrients are transported into tributaries and to the lake. Unfortunately, critical information along this continuum also is lacking in the basin. The nutrient pools and transport mechanisms can be reasonably expected to vary by subbasin, yet this is precisely the type of site-specific information necessary for planners to direct and prioritize BMPs.

The lack of comprehensive and unambiguous data on historic BMP implementation presents another barrier to a clear understanding of their effectiveness. For example, a historic record for type of BMP applied, specific location, dates of operation, and success/failure evaluation does not exist except for a few more recent projects. Without such information, stream measurements of nutrient and sediment discharge (for example) provide little insight as to the effects of a given BMP.

The series of monitoring reports issued by the LTBMU for the many and diverse projects they oversee represent a very valuable resource for the scientific community. Not only do they provide a good database for runoff water quality, they represent excellent "point-in-time" sampling, which can be used in comparisons as the projects mature. Quite often, an individual project does not come of age for a number of years. In these cases, early and routine monitoring is quite useful.

These and the other reviewed reports also bring out a number of important issues regarding the design and implementation of BMP monitoring and adaptive management.

First, unambiguous conclusions regarding the effectiveness of these projects were not always possible. The lack of long-term monitoring data typically prohibits conclusive findings. Not only do many BMPs take years to reach peak effectiveness, the imposition of hydraulic variability during a short monitoring period adds significant complications to the evaluation efforts.

Second, many BMP evaluation studies at Lake Tahoe lack reference or control sites. For example, the need for multiyear data on preproject conditions is rarely in hand before a project is started. An example where this was clearly not an issue was the Wasiu Timber Sale Project, which capitalized on a 10- to 15-year database from routine LTBMU monitoring in Meeks Creek. All things being equal, confidence in the results when this type of supporting database is available will be much higher. Because of the complex landscape in the Tahoe basin and the location of urbanized pockets of land, it is also difficult to find adequate upstream control sites.

Third, limited budgets and staff time constrain the sampling design to a point where only the most general of speculations are possible. This is not uncommon in the Tahoe basin nor in many other watersheds throughout the country. For all BMP efforts, the existing data show that well-designed and fully funded projects are needed to obtain usable conclusions. Unless the effect is dramatic, evaluating projects with limited data will yield limited conclusions.

We strongly recommended that monitoring of BMPs *not* be viewed as the sole responsibility of the implementing agency; rather, the conclusions that result are of significance to successfully restoring Lake Tahoe and must be approached from a multi-agency and interdisciplinary perspective.

Existing BMP evaluation studies show that complete water chemistry monitoring is not always feasible nor desirable, depending on the questions being asked. Photographic evidence and visual surveys may be sufficient. This is especially so for revegetation and certain erosion control projects and forms the basis for additional monitoring being considered by the USFS (Hazelhurst 1999).

Finally, most of the reviewed projects clearly show that source control should be considered the preferred option for reducing sediment and nutrient loading.

The process of identifying management issues and research needs for the Lake Tahoe basin related to BMPs and restoration has been an ongoing process. Basin agencies, university scientists, and other interested parties began to formalize this during the initial Lake Tahoe Science Symposium held in October 1998. The Research and Monitoring Subcommittee of the Lake Tahoe Basin Water Quality Group reviewed the proceedings from this symposium and assisted in developing a list of water quality-related research needs and analysis questions.

Reducing sediment and nutrient loading to Lake Tahoe is expected to be an iterative effort developed through future symposia and by basin groups collaborating with stakeholders. Some of the issues are addressed in this assessment, but many others remain to be answered. This represents a major step toward the integration of not only science and management but also toward all interested parties planning cooperatively. The success of restoration and adaptive management in the Tahoe basin depends on this type of cooperative effort.

Issue 3: Ecology, Biology and Biogeochemistry of Lake Tahoe, with Emphasis on Water Clarity

With contributions from Charles R. Goldman, Alan D. Jassby, Alan C. Heyvaert, Scott H. Hackley, Brant C. Allen, Debbie A. Hunter, Robert C. Richards, and Ted J. Swift

What has been the long-term trend for algal growth in Lake Tahoe? What are the major factors regulating the phytoplankton primary productivity?

Primary productivity is a measure of growth rate by plants. In Lake Tahoe, primary productivity is dominated by phytoplankton, the free-floating microscopic algae that inhabit the water column. The growth of attached algae (periphyton) and submersed higher aquatic plants (macrophytes) is also of concern and is discussed below. The trophic status or productivity of lakes has long been of interest, not only to water quality scientists but to water suppliers and the public at large. When uncontrolled, cultural eutrophication marks the growth of excessive quantities of algae and other aquatic plant material, loss of dissolved oxygen, loss of clarity, dominance of unwanted biota, and other characteristics that significantly interfere with a lake's beneficial uses. In many waterbodies, the unchecked addition of nutrients has resulted in an increase in fertility. Typically, it is the loading of nitrogen and phosphorus that leads to cultural eutrophication. Lake Tahoe is characterized by phytoplankton populations that are very sensitive to any increase in nutrient loading (Goldman 1990).

According to Goldman, "primary production provides the best single integration of the biological, physical, and chemical factors at work in a lake." Viewed in this manner, changes in a lake's primary productivity are almost always linked to changes in the surrounding watershed. Again, Goldman (1990) observed that since development in the Tahoe basin began to escalate in the late 1950s, phytoplankton productivity and the human population density have risen with striking similarity. Human activities that have led to the increased loading of nutrients and sediment from either the watershed or airshed are linked to the decline of water quality at Lake Tahoe.

Nationally, and specifically at Lake Tahoe, considerable sums of money have been spent to reduce nutrient inputs by controlling wastewater discharge, agricultural drainage, and, most recently, nonpoint source runoff. Once classified as severely lacking in plant nutrients (ultra-oligotrophic), Lake Tahoe has been moving away from its unique pristine nature for many decades. The pioneering work of Dr. Charles R. Goldman and his colleagues at the University of California, Davis, has been instrumental in identifying the onset of cultural eutrophication in Lake Tahoe in the late-1960s and early-1970s, in documenting the long-term trend, in relating nutrient loading to increases in algal growth rate, and in identifying sources of nutrients to the lake. Phytoplankton primary productivity, along with its relationship to lake clarity, has been fundamental to most water quality management policies in the Tahoe basin, including the exportation of sewage and the need for watershed restoration. The water quality thresholds established by TRPA include a standard for annual mean phytoplankton primary productivity of 52 g $C/m^2/yr$. This reflects levels measured from 1967 to 1971. Neither this initial value or the interim target of 145 g $C/m^2/yr$ for Water Year 1995 are being met.

The first measurements of phytoplankton growth in Lake Tahoe were carried out in 1959. At that time, the annual rate was slightly less than 40 g $C/m^2/yr$ and typical of an ultra-oligotrophic status. For years prior to 1959, average annual primary productivity was reconstructed from an analysis of deep lake sediment cores. Heyvaert (1998) concluded that the baseline predisturbance (prior to 1850) primary productivity was 28 g $C/m^2/yr$. Interestingly, his calculations for the period from 1900 to 1970, a time between the effects of the Comstock logging era and the onset of urbanization, was identical to the baseline at 29 g $C/m^2/yr$. Both these values were only 25 to 30 percent less than the earliest measurements in 1959. As discussed below, the virtual recovery to baseline conditions following the extensive timbering activities during the Comstock Era provides evidence that Lake Tahoe can recover from watershed disturbance.

The annual primary productivity of Lake Tahoe has more than quadrupled since 1959 with recent measurements exceeding 160 g $C/m^2/yr$ (Figure 4-20). Annual estimates are based on measurements taken at 13 individual depths (0 to 105 m) on approximately 35 dates throughout the entire year. Goldman (1988, 1992) reported that although there is some year-to-year variation, a second order polynomial fit to the productivity data shows a highly significant trend ($p<0.001$). This trend continues to increase at a rate of approximately five to six percent per year. While the primary productivity values for successive years might decline, only twice has this decline occurred for two consecutive years, 1975 to 1977 and 1980 to 1982. The largest single-year increases were found in 1983 (28 g $C/m^2/yr$ or 32 percent), 1989 (30 g $C/m^2/yr$ or 25 percent), and 1993 (33 g $C/m^2/yr$ or 22 percent). Curiously, the magnitude of these three large annual increases was very similar to baseline conditions during the early part of the 20th century. This highlights the impact that nutrient loading has had on Lake Tahoe. As noted by Goldman (1988) for the 1983 increase, the 1989 and 1993 increases also occurred when total lake mixing was accompanied by heavy precipitation and runoff. As discussed below, the fundamental reason for the long-term trend in phytoplankton growth is accumulation of nitrogen and phosphorus from both watershed runoff and atmospheric deposition.

Causes of Eutrophication in Lake Tahoe

The causes of long-term increase in primary productivity in Lake Tahoe are attributable to increased nutrient loading acting in concert with the lake's long retention time and efficient recycling of nutrients (Goldman 1988). Bioassays of Lake Tahoe water have linked nutrient additions to stimulated algal growth. Many factors contribute to nutrient loading at Lake Tahoe, such as land disturbance, urbanization, increase in impervious surfaces, erosion, atmospheric deposition, fertilizer application, ground water, and loss of such natural filters as wetlands and riparian corridors.

An early study by Paerl (1973) provided the first evidence that much of the bioavailable particulate organic matter in Lake Tahoe is decomposed before settling to the bottom. Using scanning electron microscopy, he observed that at shallower depths (20 m) there was a close association between bacterial and fungal cells and detrital or decomposing organic material, much of which is presumed to be phytoplankton. At deeper depths (75 m) microbial growth on these particles was much reduced. Between 150 and 400 m there was little change to the structure of the microbial association with detritus. At these depths there was little microbial attachment. Paerl concluded that detritus settling on the bottom of Lake Tahoe appeared to be unreactive because it was attacked by only a small amount of bacteria.

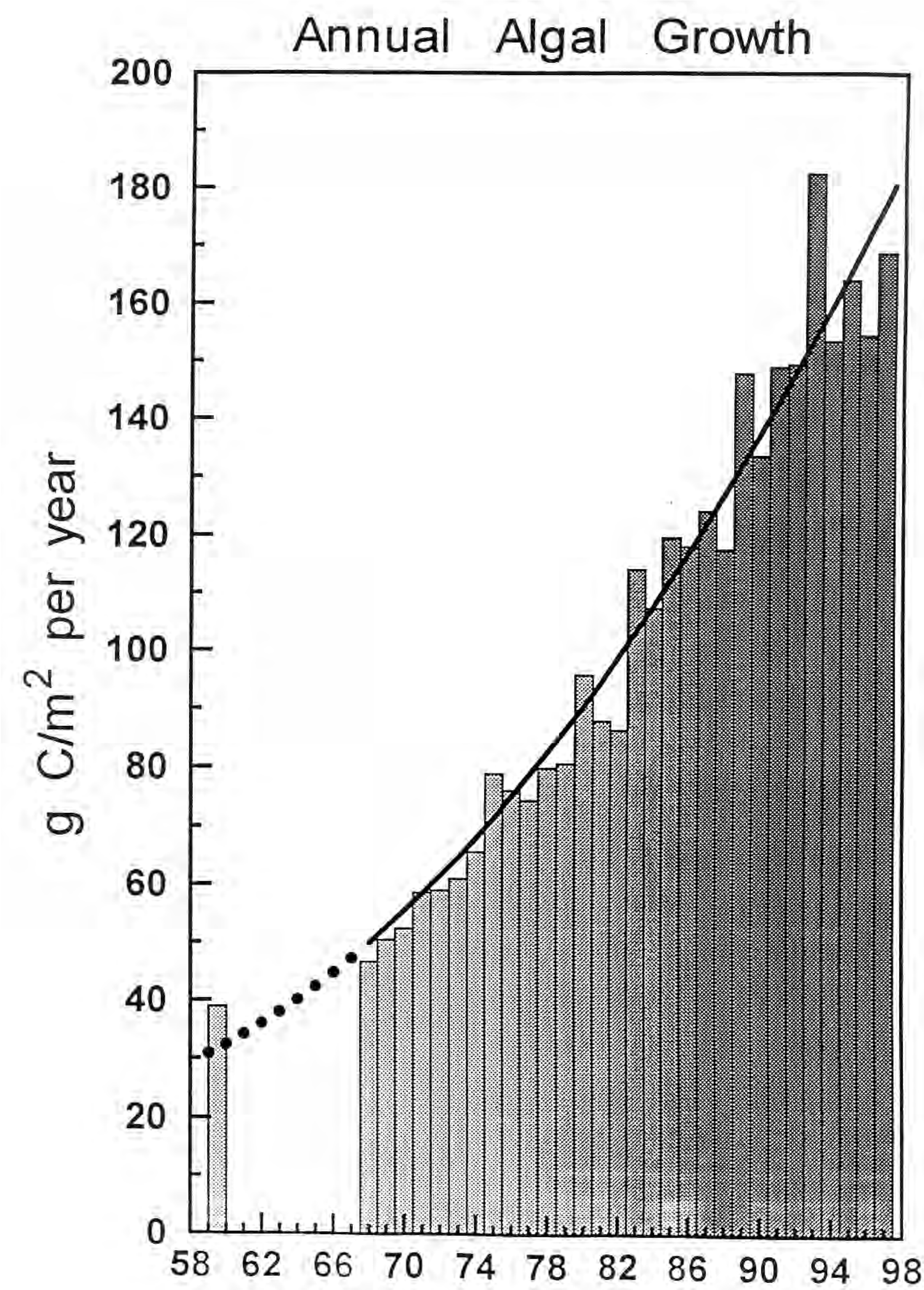


Figure 4-20—Long-term trend of increasing algal growth rate in Lake Tahoe.

Given the continual and increased loading of nutrients to the lake, plus the effective recycling of a large portion of the bioavailable fraction contained in phytoplankton and other organic matter, the accumulation of nutrients in Lake Tahoe is likely. This steady accumulation is believed to have led to the observed long-term increase in primary productivity. The increases in primary productivity initially were fueled by atmospheric deposition of nitrogen (Jassby et al. 1994); however, with the increased sensitivity of algal response to phosphorus, the most appropriate courses of action are careful management of development and land use, restoration of existing erosion problems, purchases of sensitive lands, and treatment of urban surface flow .

Interannual Fluctuations in Primary Productivity: Meteorological Forcing

Goldman et al. (1989) provided an explanation for the year-to-year variability seen around the long-term trend. These authors reported a close relationship between maximal spring mixing depth and the interannual variability seen around the long-term trend. Vertical mixing is known to be critical in maintaining a lake's productivity level. Goldman et al. found that "our data indicate that the intensity of vertical mixing not only maintains a characteristic trophic state, or level of production, but also, through year-to-year variability in maximum mixing depth, is tightly linked to interannual fluctuations about this level." Since 1973, deep-mixed years (turnover >400 m) include 1973 to 1975, 1983, 1985, 1989, 1993, possibly 1997, and 1998. During other years, the lake mixes from between 100 m to 300 m, with a median value of approximately 200 m.

Goldman et al. (1989) developed a model of depth of mixing versus primary productivity after first statistically "pre-whitening" the data to remove the upward trend. This de-trending removes autocorrelations in the data (Goldman 1990). The results were significant ($p<0.05$). Depth of mixing, when used as the single predictor, accounts for 53 percent of the interannual variability (Figure 4-21).

Annual primary productivity in Lake Tahoe did not exhibit anomalous behavior during El Niño years. That is, phytoplankton growth rate during these years was typically within ± 1 standard error of the regression describing the long-term trend. Furthermore, the depth of mixing appeared best correlated with March precipitation ($p<0.05$). According to Goldman et al., the significance of these findings is that when the water column at Lake Tahoe is near a condition where the temperature is uniform from top to bottom (around March), a single intense storm can cause a complete mix. With regard to lake mixing during a rather narrow window of time (about a month), the impact of El Niño years (whether wet or dry) are typically felt over a period of many months.

The stimulation of primary productivity by spring mixing is related to the return of regenerated nutrients from deep waters to the euphotic zone. For example, prior to mixing, deep-water nitrate can reach a concentration of from 20 up to >35 μg N/L . This is in contrast to summer euphotic concentrations of 1 to 2 μg N/L, reduced as a direct result of algal uptake. To appreciate the magnitude of internal loading of nutrients from the aphotic (receiving insufficient light for plant growth) and deeper waters in Lake Tahoe to the euphotic zone during mixing, internal loading can range from between one and two orders of magnitude (10 to 100 times) higher than the combined external loading from watershed runoff and atmospheric deposition (Byron and Goldman 1986). Clearly, in light of the long resident times for nitrogen and phosphorus in Lake Tahoe, the progressive accumulation of nutrients in the lake can remain available to fuel algal growth for many years.

Finally, other studies have shown that algal cells in the deep waters of Lake Tahoe are viable and capable of photosynthesis once reintroduced into the euphotic (receiving sufficient light to support percent growth) zone. This raises the possibility that spring mixing events also inoculate the surface water with phytoplankton (Tilzer et al. 1977; Vincent 1978; Goldman and Jassby 1990).

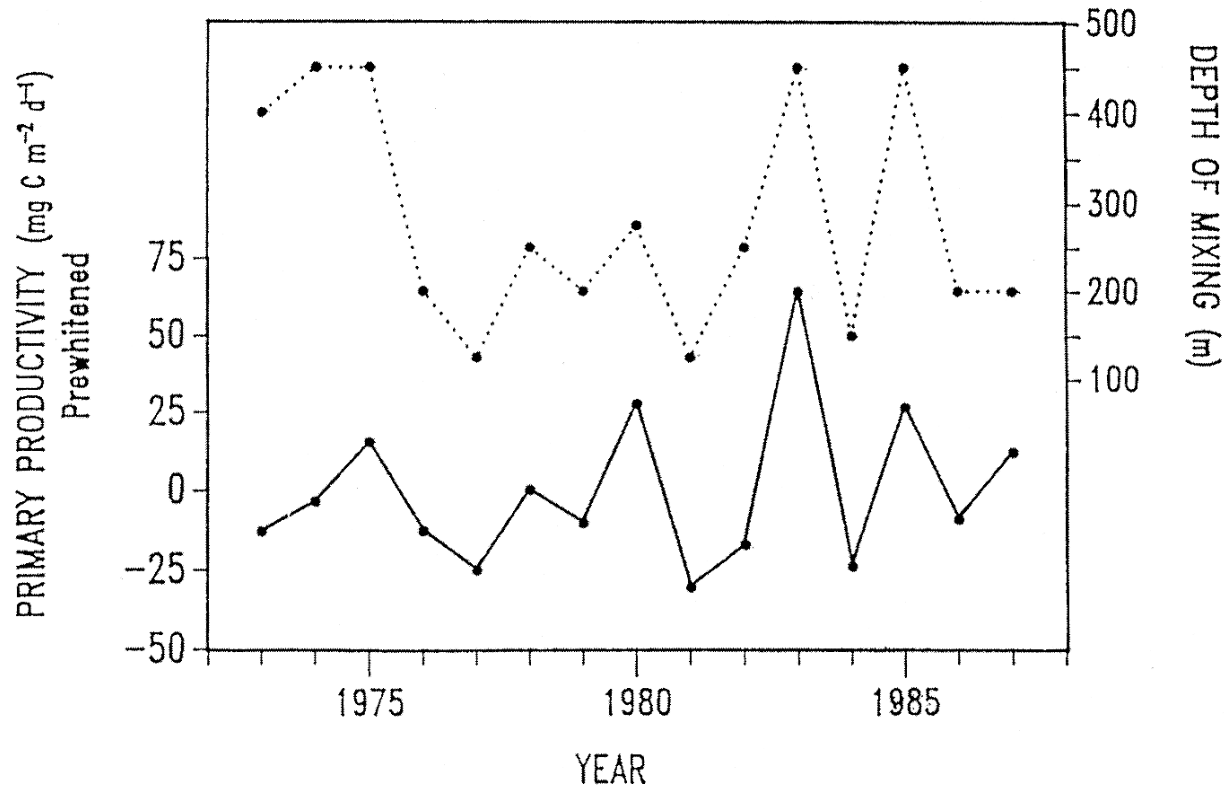


Figure 4-21—Depth of mixing in the winter-spring exerts a significant influence on the year-to-year variability in primary productivity (from Goldman et al. 1989).

Seasonality, Cycles, and Irregular Fluctuations in Primary Productivity

Jassby et al. (1992) have described a number of mechanisms underlying variability in the productivity record. The material presented in this section is taken from that publication.

Seasonality—The basic time-series of monthly primary productivity exhibits strong seasonality in addition to the significant upward trend. The standard deviation of the monthly values is proportional to the annual mean, thus the difference between the seasonal maximum and minimum also has increased. Jassby et al. (1992) extracted a typical seasonal cycle from the mean monthly primary productivity series, which was statistically adjusted to account for the dominating upward trend (Figure 4-22). Seasonality at Lake Tahoe also has been discussed in several other publications (e.g., Goldman and de Amezaga 1975; Goldman 1981). The seasonal pattern is marked by a monthly median peak in July and a minimum in January. Median primary productivity increases between January and May, remaining relatively uniform between May and August. This seasonal pattern follows the annual solar cycle with a lag of one month. Seasonality on the whole was subdued, with less than a factor of two difference between the highest and lowest median monthly values. The mechanisms driving seasonality are primarily physical and apparently are not related to trophic cascade or food web dynamics (Jassby et al. 1992). Little feedback occurs from the sparse mesozooplankton populations (Elser et al. 1990), and the seasonal nature of primary productivity is regulated primarily by the interaction of the solar cycle with lake stratification. The role of bacterial and microbial grazers is unstudied in Lake Tahoe, and Jassby et al. note that a different view of the role of grazing may emerge as information on the microbial loop becomes available.

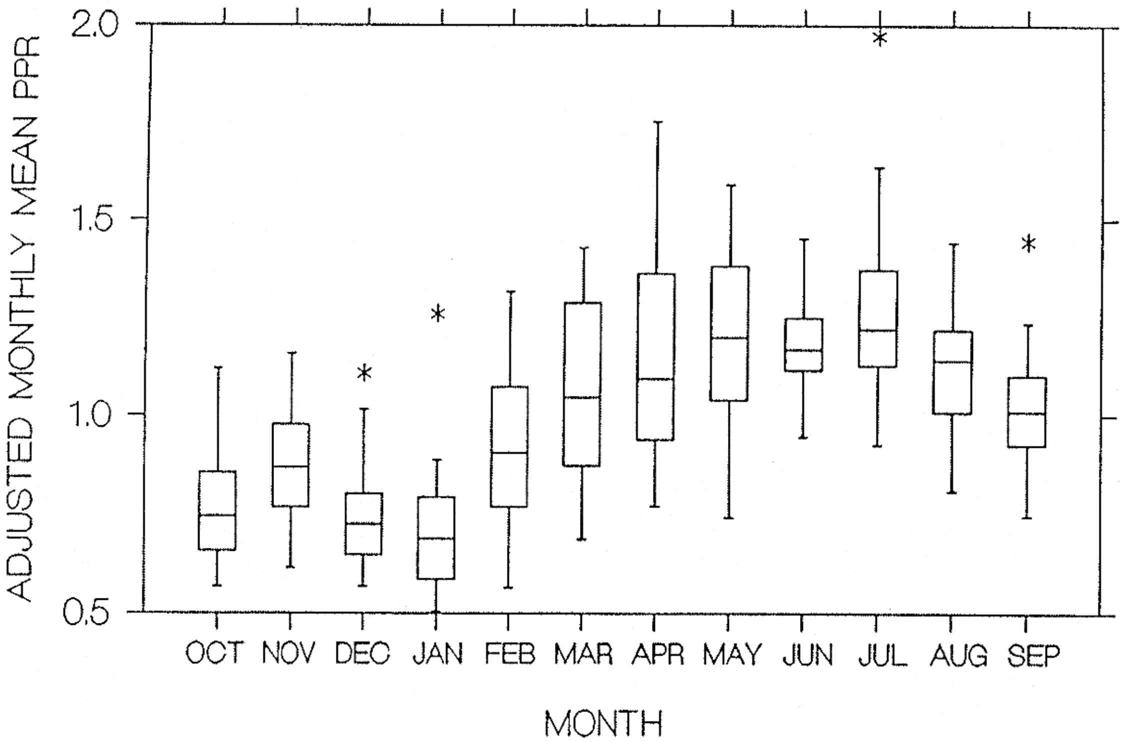


Figure 4-22—Seasonal pattern for month mean primary productivity in Lake Tahoe using historical database (from Jassby et al. 1992).

Cycles—Jassby et al. (1992) also uncovered the existence of a three-year cycle in primary productivity using more sophisticated tools of data analysis such as Principle Components Analysis (PCA) and spectral analysis (Figure 4-23). The reason for this cycle was not established; however, the authors considered several mechanisms. No cycles of similar period were apparent in meteorological conditions at Lake Tahoe. Solar radiation and water temperature did not show patterns greater than one year in length.

Regular oscillations can arise from the interactions of phytoplankton species and their limiting nutrients. Data on individual phytoplankton species are not sufficiently detailed at this time to look for multiyear cycles in the numbers or biomass of individual taxa.

Cyclical patterns in primary production can be generated by oscillations at higher trophic levels, for example, grazers with a three-year generation time. While the reported lack of significant grazing control by zooplankton on phytoplankton at Lake Tahoe discourages this as an explanation, the opossum shrimp (*Mysis relicta*) has been hypothesized to play a significant role in the downward transport of nutrients during their daily vertical migrations between the surface and bottom waters (Rybock 1978; Marjanovic 1989). According to estimates given in Jassby et al. (1992), *Mysis* can ingest nitrogen on the order of all of the available N in the euphotic zone. Because a significant portion of ingested material is excreted at depth, *Mysis* could clearly influence nutrient availability and primary productivity. With a generation time of two to three years (Levitan 1999) *Mysis* might be a likely explanation of the three-year cycle in primary productivity. However, no statistically significant cycle could be discerned from the *Mysis* density series obtained from vertically towing the water column. Jassby et al. suggest that these complete vertical tows do not distinguish between migrating and nonmigrating animals, resolution of this awaits further study.

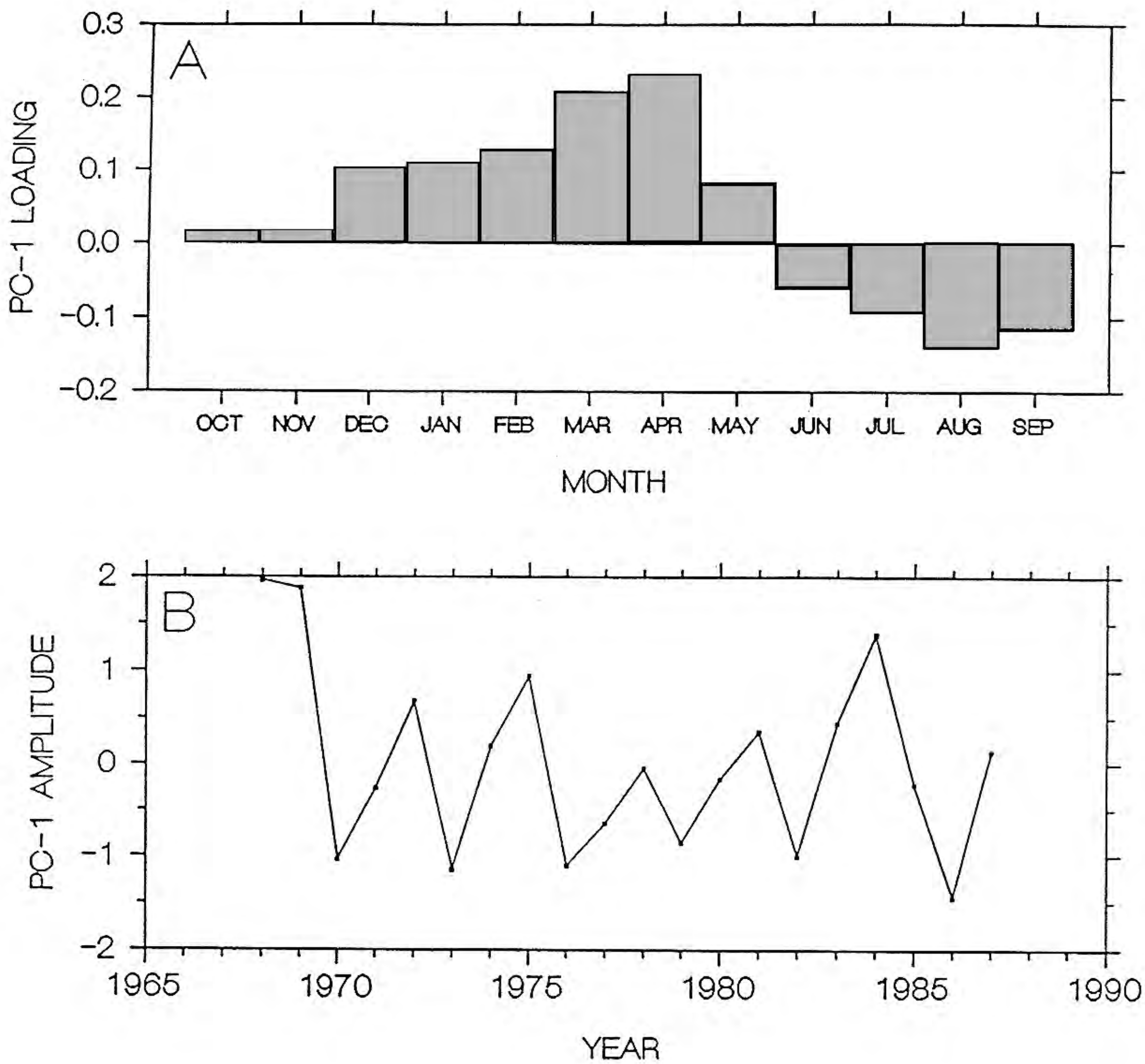


Figure 4-23—Principle components analysis of long-term primary productivity data indicating a consistent three-year cycle (from Jassby et al. 1992).

Irregular Fluctuations—This includes variability that does not belong to the categories discussed above. For example, the 1985 Wheeler fire in the Los Padres National Forest in southern California had a marked stimulatory effect on Lake Tahoe primary productivity in July of that year (see below). While the contribution of these isolated events is not necessarily important to the variability of the long-term record, they can have significant impacts on the timing and magnitude of primary productivity during that year. As discussed below, if forest fires become a more frequent feature in the Tahoe basin, they cease to be isolated events and need to be factored into considerations of the long-term trend in phytoplankton growth.

A second category of irregular fluctuations includes annual phenomena with irregular magnitudes. As discussed above (Goldman 1988; Goldman et al. 1989; Goldman and Jassby 1990), the depth of spring mixing falls into this category.

Forest Fires, Atmospheric Deposition, and Primary Productivity

The effect of forest fires on lakes in the western United States is not well known. Even those few studies that have been done elsewhere suggest that the response of lakes to increased runoff can be mixed. Fires also can modify the light climate through smoke production and can contribute products of combustion to the atmospheric deposition on lake surfaces. Goldman et al. (1990) directly documented this phenomenon at Lake Tahoe, providing further documentation for the link between atmospheric pollution and its effect on Lake Tahoe water quality and primary productivity. The discussion below is based on that study.

On July 1, 1985, the largest fire in the US occurred in the Los Padres National Forest in southern California, burning nearly 50,000 hectares of brush. Smoke from this fire clouded the southern part of the state and traveled in a dense plume northward to the Tahoe basin. Air quality at Lake Tahoe was visibly affected by this smoke, suggesting a possible impact on Tahoe's unproductive waters. Visibility decreased by July 3, and the entire basin was covered in smoke by July 11. At that time, surface irradiance declined by a factor of two, and photosynthetically active radiation penetrating into the lake was reduced even further due to the settling of ash particles into the water.

The effect of this event was a large increase in primary productivity. Algal growth increased by more than a factor of three with a rise in the depth of the mixed layer peak from 10 to 15 m to 5 m (Figure 4-24). A second and deeper peak in productivity, which is typically found below the thermocline at a depth of 50 to 70 m disappeared at this time. Since Secchi disk clarity is measured only within the upper 20 to 30 meters, any change in the distribution of primary productivity could affect clarity. While a release from photoinhibition in the surface waters could explain the change in the vertical distribution of primary productivity, Goldman et al. reported that it does not account for the dramatic increase in photosynthesis. Similarly, because phytoplankton biomass did not change appreciably during this period, Goldman et al. (1990) concluded that "productivity increases during the fire thus are due to a true stimulation of photosynthetic activity and (do) not reflect only changes in biomass or a reduction in light inhibition."

Experimental evidence suggests that nutrients contributed by dry fallout during the fire were the likely cause of the observed increase in primary productivity. Using algal bioassay procedures, the authors found a stimulation in primary productivity when atmospheric filtrate from the July fire was added to Lake Tahoe water. This stimulation was similar to that resulting from the addition of phosphorus and nitrogen; that is, photosynthesis was approximately 140 percent of the control (Figure 4-25). Previous bioassays using fallout from atmospheric deposition showed no stimulation in the absence of forest and brush fires. Observations of Lake Tahoe water using microscopic techniques revealed the presence of numerous small particles on the order of 10 μm in size, presumably deposited during the fire. Leaching of nutrients from these particles was suggested but direct tests were not made.

The impact of the fire also was evaluated in the context of the long-term primary productivity record for Lake Tahoe. This analysis clearly showed that the high values in 1985 were anomalous for the month of July. While not as pronounced, there was some indication of an effect on annual productivity. As mentioned above, the effect of fires on the long-term trend of increasing productivity has been trivial; however, increased fire frequency is likely to have an effect.

Recent but limited data suggest that coniferous forest fires in the vicinity of Lake Tahoe may be much less fertilizing than the 1985 brush fire (Goldman 1999). Even though atmospheric deposition did stimulate phytoplankton response, there was no significant difference between deposition collected during smoke and smoke-free periods.

What is the long-term trend for water clarity in Lake Tahoe and how is clarity affected by phytoplankton and suspended mineral sediment?

Optical clarity is important in making judgments about water quality. Indeed, it was the combination of increasing primary productivity and decreasing clarity that documented the onset of cultural eutrophication in Lake Tahoe (Goldman and de Amezaga 1975; Goldman 1981, 1988, 1999). Much of the public concern regarding priority issues

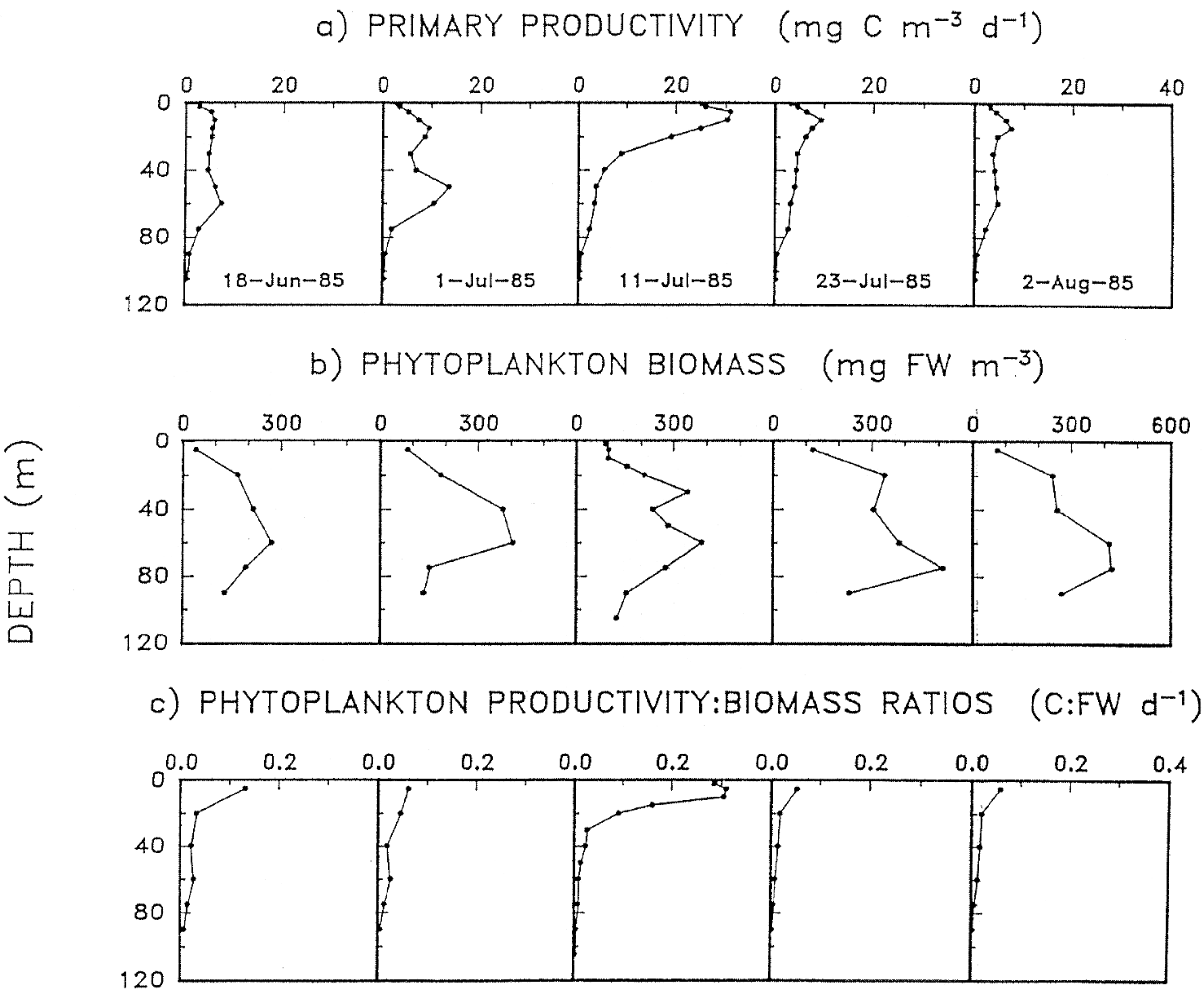


Figure 4-24—Effect of fire in Los Padres National Forest in southern California on primary productivity in Lake Tahoe. Notice change in the bimodal profile on July 11, when the effect was greatest (from Goldman et al. 1990).

at Lake Tahoe focuses on lake clarity. In a survey taken by Senator Barbara Boxer in September 1997, lake clarity was identified as the number one concern by over a third of the respondents and was 68 percent higher than the runner-up. The public is very aware of the long-term decline in clarity and this topic is frequently discussed in public forums and in the local and regional newspapers. TRPA also has established a water quality threshold for clarity. The adopted standard is that average Secchi depth, December to March, shall not be less than 33.4 m. Currently this standard is not being attained.

Water clarity is an excellent indicator of lake response in Lake Tahoe and has been measured using a Secchi disk since 1968. Not only have the historic Secchi data provided water quality scientists with an important understanding of lake function and response, they embody the issue of changing water quality at Lake Tahoe in an easily understood fashion. The importance of this database and that for primary productivity is recognized by resource policy-makers, environmental scientists, the judiciary (Garcia 1984), and the public.

Le Conte (1883) was the first to measure the clarity of Lake Tahoe with a Secchi disk. In

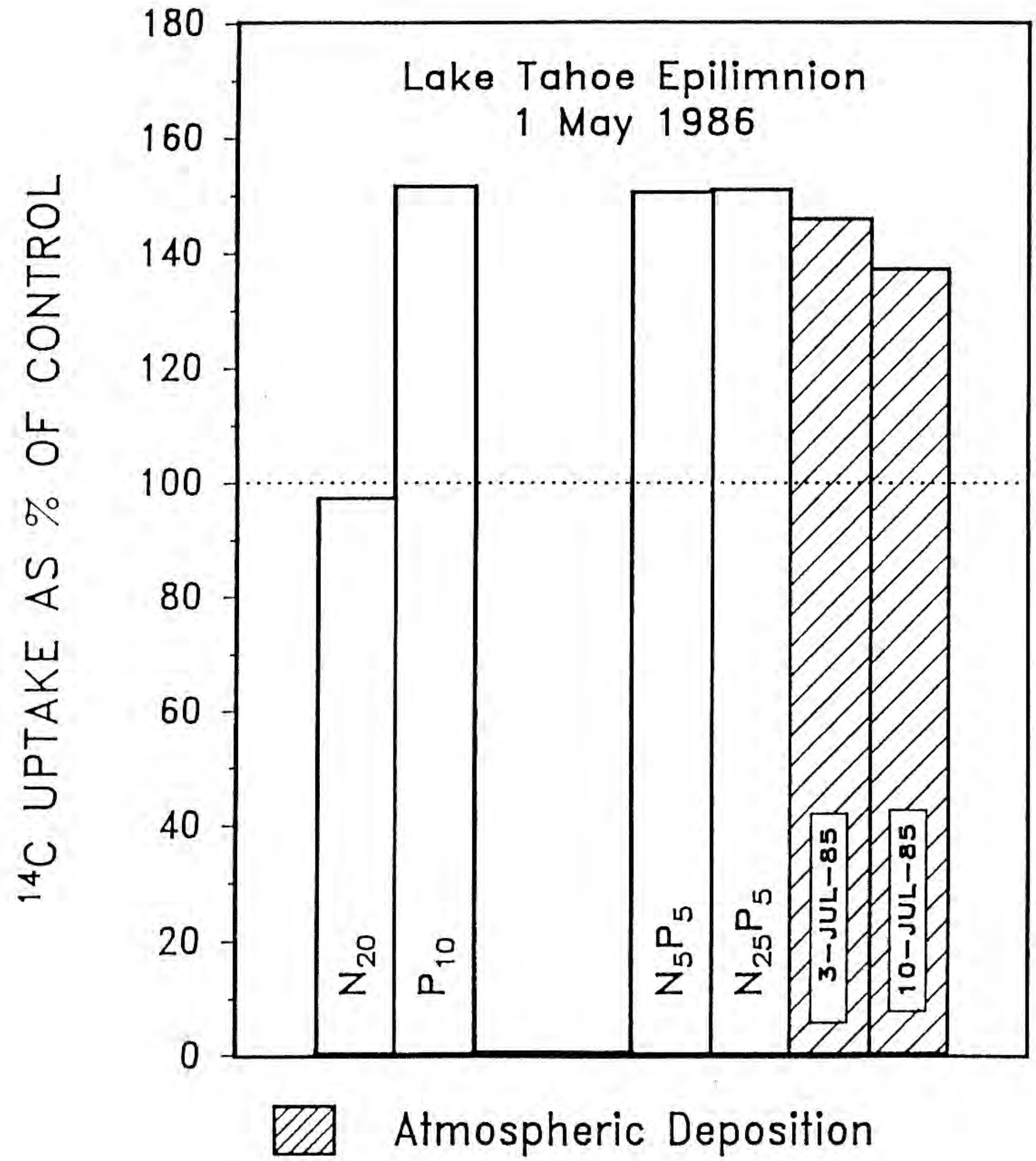


Figure 4-25—Leached nutrients from dry fallout during the Los Padres fire stimulate primary productivity in algal bioassay experiments (from Goldman et al. 1990).

September 1873 he recorded a value of 33 m using a 24-cm plate; today, a 20-cm disk is used. Secchi depth measurements ranged from 24 to 32 m in 1959 and 33 to 36 m in 1960. During these initial years, measures were too infrequent to calculate an annual average. Goldman (1988) summarized the Secchi depth data through 1986 in his key paper on early eutrophication in Lake Tahoe. The 30-year database for annual average Secchi depth is shown in Figure 4-26. As observed for primary productivity, a highly significant ($p<0.001$) long-term trend in lake clarity can be seen despite interannual variability. Individual single measurements of Secchi depth in Lake Tahoe over the period of record have ranged from as great as 43 m during an upwelling event on February 8, 1968, to as low as only 8.5 m on June 1, 1983, during a wet El Niño year. The lowest recorded measurements are associated with years of deep lake mixing and high surface runoff. The lake water appeared green when the 8-m value was measured. This provides strong evidence that the lake has the capacity to reach these unwanted conditions and underscores the urgent need for restoration efforts. As part of the material prepared for the 1997 Presidential Forum, Goldman and Reuter (1997a, 1997b, 1997c) stressed that if the decline in lake clarity continues over the next 30 years at the same rate it has over the past 30 years (approximately 0.25 m per year) the resulting transparency will be on the order of 12 to 13 m. A change of this magnitude has already occurred in the polluted regions of Russia's Lake Baikal (Goldman et al. 1996).

An important lesson contained in the long-term Secchi depth data is that by using a short-term subset of even five to six years, it is easily possible to arrive at a totally incorrect interpretation of the data (Goldman 1993). Goldman has effectively emphasized on numerous occasions that had the measured water clarity data from Lake Tahoe during the period 1973 through 1977 or 1983 through 1988 been used to assess the status of Lake Tahoe, one would have erroneously concluded that lake clarity was actually improving (Figure 4-27). For 1983 to 1988, the increase in clarity was even statistically significant ($p<0.01$). In fact, the apparent improvement was only short-term due to the combination of reduced runoff and an absence of deep mixing during drought years. Well-planned and executed, consistent and long-term monitoring insured that these types of interpretation mistakes were not made at Lake Tahoe. This conclusion is not only important for lake clarity but must be considered during discussions of design and implementation for future monitoring at Lake Tahoe.

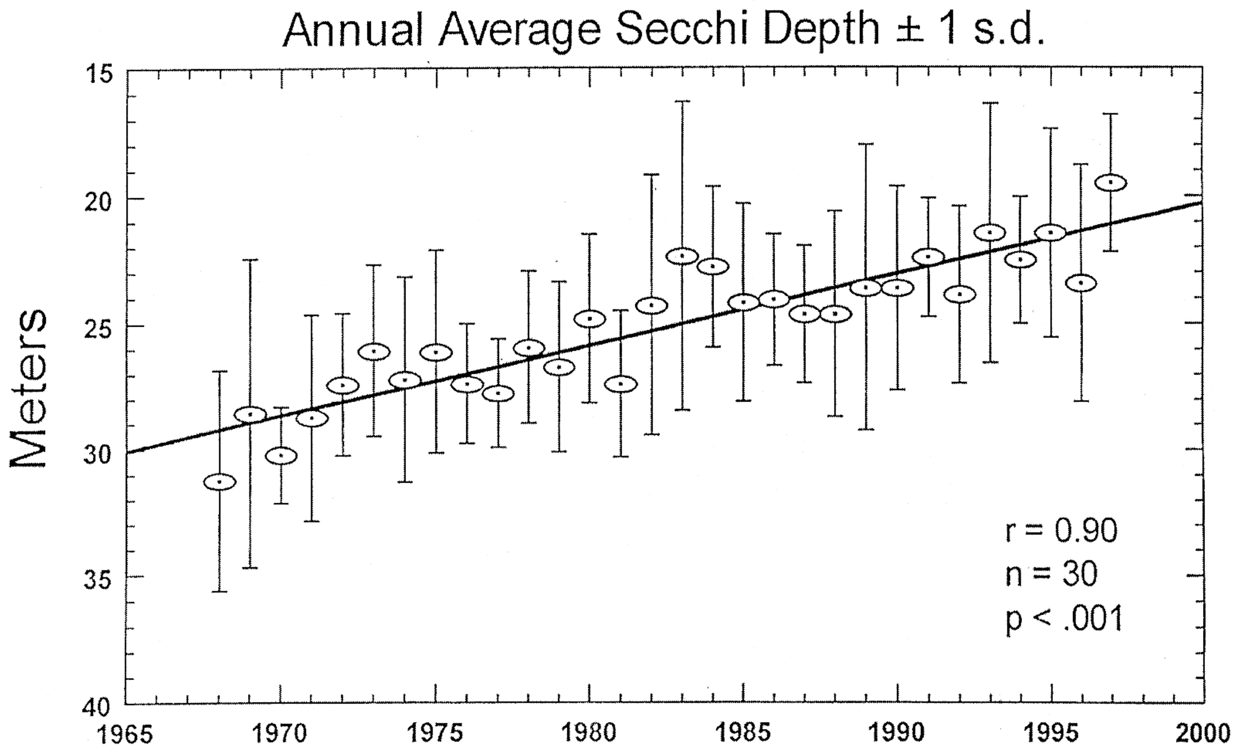


Figure 4-26—Average annual Secchi depth at the TRG index station through 1997. Each year represents the mean of observations taken every 10 to 15 days throughout the entire year.

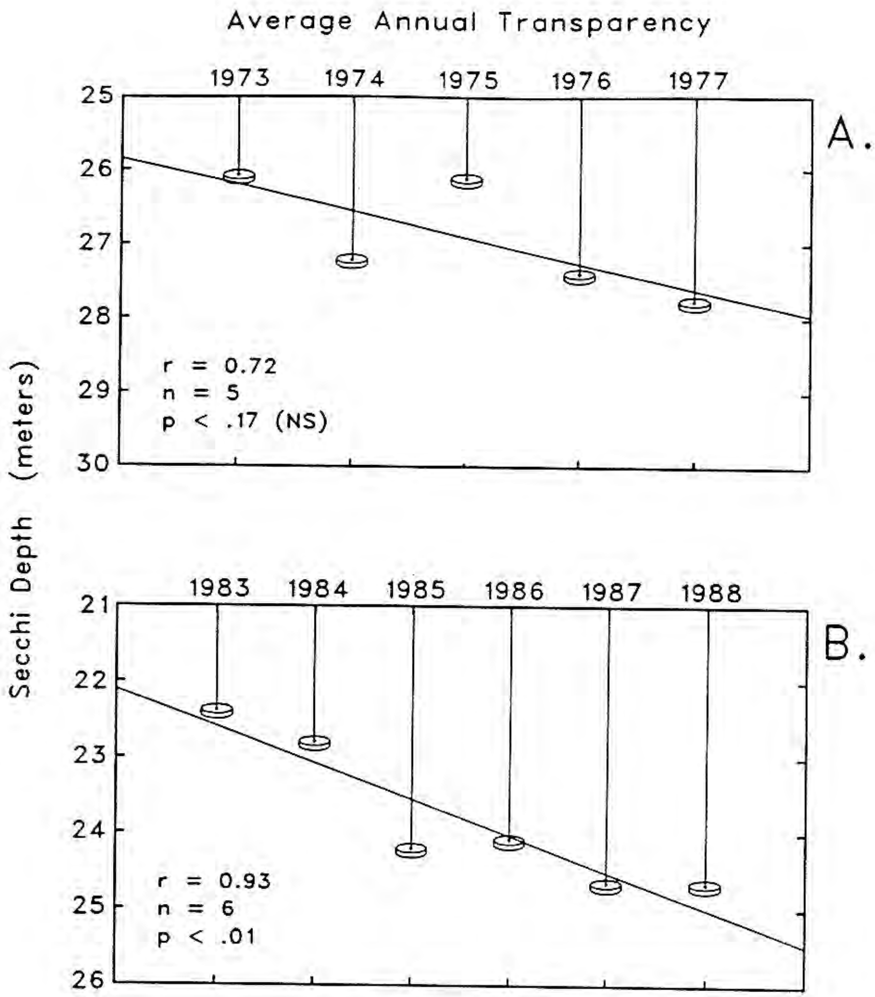


Figure 4-27—Analyzing isolated segments of the long-term clarity database can lead to false conclusions regarding trend in transparency (from Goldman 1993).

Explaining Long-term and Other Scales of Temporal Variability in the Transparency of Lake Tahoe: The Contribution of both Phytoplankton and Suspended Fine Sediment

The simultaneous increase in primary productivity and decrease in clarity strongly implicates the role that nutrient loading has had on the long-term decline in Secchi disk measurements, that is, on increased algal growth. However, even large lakes are subject to influence by fine sediment particles derived from the surrounding watershed. Until recently, the contribution of these terrestrially derived particles, such as silts and clays, has not received as much attention as the phytoplankton component. Many substances contribute to light absorption and scattering and, consequently, the reduction of clarity. Based on origin, these can be categorized as water molecules, phytoplankton plus detritus recently derived from phytoplankton, material produced in the lake but not containing photosynthetic pigments (including bacteria, viruses, dissolved and particulate organic matter, and biogenic minerals), and materials derived from out-of-lake sources, especially mineral suspensoids from erosional or aeolian fine sediment.

Jassby et al. (1999) have recently published an analysis of the origins and scale dependence of temporal variability in the transparency of Lake Tahoe from 1968 to 1996. The primary objective of this study was to establish the dominant modes and causes of seasonal, year-to-year, and decadal variability in lake clarity according to the measured Secchi depth time series of 29 years. This time series is of sufficient resolution and exhibits characteristics that enable some differentiation to be made among the various categories of light-attenuating factors cited above. Jassby et al. also employed a shorter time series for chlorophyll *a* (the major algal pigment and an estimate of biomass) and recent measurements of suspended particulate matter. Figure 4-28 shows the relationship between "contract attenuation" and Secchi depth. Increasing contrast attenuation corresponds to an increase in materials in the water that reduce light penetration. In a more dilute waterbody, such as Lake Tahoe, very small increases in these materials can result in large changes in Secchi depth.

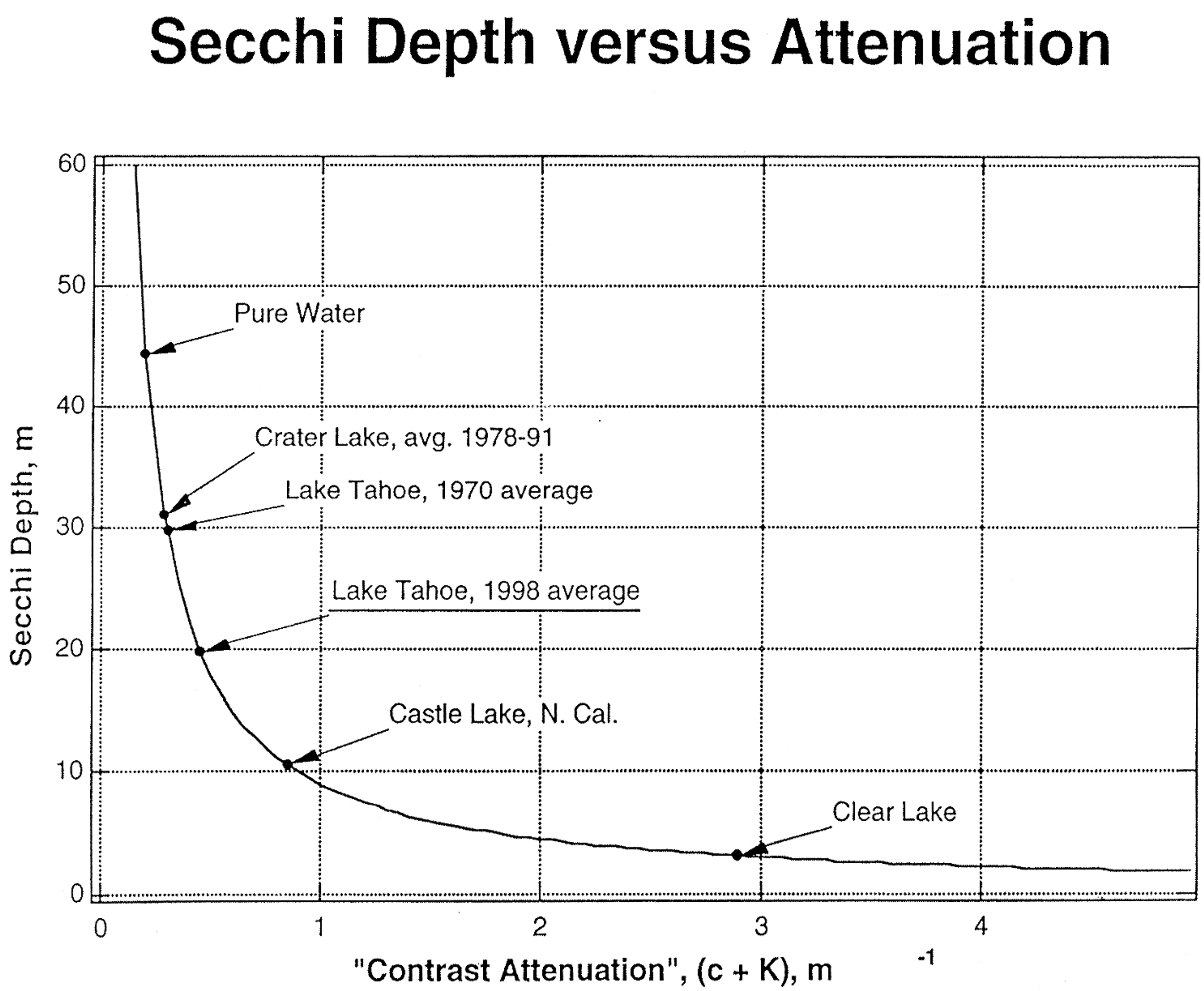


Figure 4-28—Relationship between Secchi depth and contrast attenuation. The contrast attenuation is a function of material in the lake, which reduces light penetration. In dilute waterbodies, such as Lake Tahoe, small changes in the amounts of these materials can have large effects on Secchi depth.

Long-term Trend

The monthly time series at the index station exhibits considerable variability at the seasonal scale. Filtering the data to remove this seasonal effect and to accentuate variability at longer time scales, Jassby et al. (1999) found lake clarity to be dominated by a long-term decreasing trend, similar to previous analysis using average annual values. This trend was highly significant ($p<0.0025$), with a slope of -0.25 m/yr. While this study reports that this decreasing trend was due mostly to changes before 1985, the analysis did not include 1997 and 1998, which corresponded to the two lowest annual average Secchi depths on record, 19.6 m and 20.1 m, respectively. Prior to these last two years, monthly Secchi values only infrequently dipped below 20 m. Additionally, the early portion of the post-1985 period was characterized by an extended state-wide drought. In the seven years between 1986 and 1992, the lake mixed completed only in 1989.

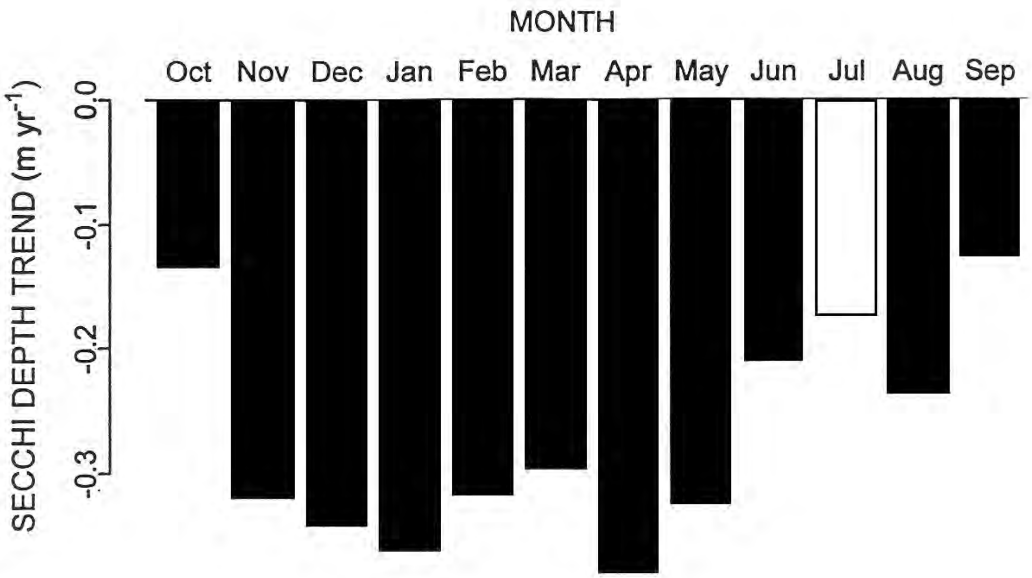
According to Jassby et al., "the long-term (decadal-scale) change in Secchi depth appears to be due to an accumulation of materials in the lake." This is a critical observation from the perspective of lake and watershed management. The importance of reducing particulate matter cannot be overemphasized. This particulate matter either enters Lake Tahoe by surface runoff/stream discharge from the watershed (primarily eroded soil sediment) or is produced in the lake as phytoplankton that use nutrients loaded either from watershed runoff or from atmospheric deposition.

Jassby et al. (1999) addressed the issue of the nature of the accumulating particles and in particular, chlorophyll-associated materials versusinorganic sediment. Using the regression model developed from the 1995 to 1997 field measurements of Secchi depth, chlorophyll, and total suspended solids, it was concluded that either phytoplankton-derived materials or mineral suspensoids could have explained the decline in clarity. The database needed to more accurately determine the relative contribution of these materials is simply too short to allow for an unambiguous answer. However, the authors did hypothesize a significant role for mineral suspensoids, emphasizing that fine inorganic sediment in the size range of 0.5 to 2 μm have the highest light scattering efficiency and that particles in this size range might not settle to the bottom before being resuspended by mixing or other forms of vertical exchange. Based on stream sediment loading data from the Lake Tahoe Interagency Monitoring Program's database, these authors concluded that "only a small fraction of cumulative suspended sediment from just one source [the Upper Truckee River] needs to be retained in the water column to account for loss of clarity."

Ultimately, the recovery of Lake Tahoe clarity depends on the rate at which the supply of suspended particulate matter can be reduced in relation to the effective rate of loss of material from the water column. Management can significantly influence the former; the latter (sedimentation rate) is beyond the control of this group, in Lake Tahoe. These results suggest that it is not enough to simply institute erosion control measures that target total suspended sediment if the smaller particles are allowed to get through unabated. If smaller mineral suspensoids are in fact important in the observed long-term decline in lake clarity, evaluating the success of erosion, dust, and other sediment control projects simply by the bulk amount of material retained may result in lake clarity improving far less than anticipated. Clearly, further studies are required to delineate the roles of these different light-attenuating materials. It would be particularly valuable if monitoring and research on sediment loading and BMP effectiveness included a component for particle size determination.

Seasonal Variability

Not only was the overall long-term trend in clarity negative but so were the long-term trends for each of the individual months (Figure 4-29). All were statistically significant, save that for July. The rate of clarity loss was less during the months of stratification from June to October (-0.1 to -0.2 m/yr) relative to the remaining months ($\geq$ -0.3 m/yr). The mean seasonal pattern over the period of record was bimodal, with a strong annual minimum Secchi depth in approximately June and a weaker local minimum in December. The overall maximum



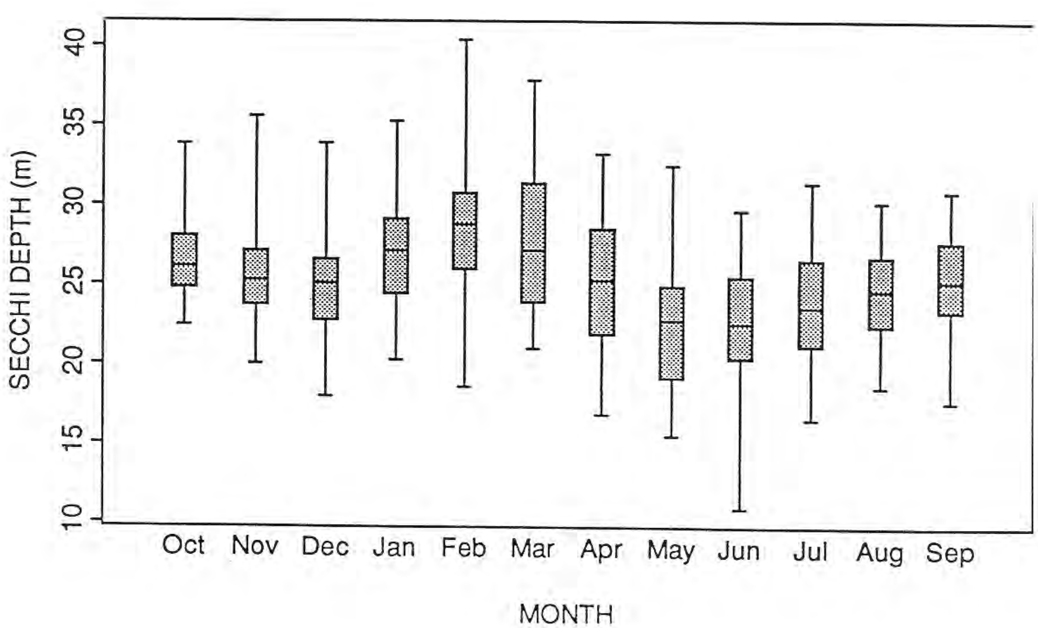


Figure 4-29—Upper panel shows trend in loss of clarity in Lake Tahoe for individual months. Lower panel combines the long-term Secchi depth record to show the seasonal pattern of clarity. Note reduced clarity in May-June and December (from Jassby et al. 1999).

was in February, with a secondary local maximum in October. Secchi measurements at the mid-lake station were less frequent (approximately a monthly schedule), but the time series for both stations were similar. Mean annual Secchi depth at mid-lake is commonly from 0 to 2 meters deeper than the index station, which is closer to shore.

Jassby et al. (1999) considered the June minimum in Secchi depth to be due to the cumulative discharge of suspended sediment following melting of the seasonal snowpack (Figure 4-30). This was found to be consistent with the measured seasonal pattern of suspended sediment discharge and with visual observations of sediment plumes entering the lake. For example, if the 8.85 tons per day average suspended sediment discharge from the Upper Truckee River from 1972 to 1988 were distributed evenly over the entire 0-30 m stratum of the lake, this rate is equal to 0.23 mg/L in a single year. A change of only 0.1 mg/L could account for a 5 to 10 m change in Secchi depth, which is the magnitude of the seasonal change. As the sediment load diminishes in June and thermal stratification intensifies, the balance between watershed inputs and outputs by sedimentation begins to shift, resulting in the gradual increase in clarity from June to October.

The December minimum was attributed to the deepening of the mixed layer as the thermocline erodes at that time of year and passes through layers of phytoplankton and other light-attenuating particles, which reach a maximum below the summer mixed layer, e.g., the deep chlorophyll maximum that is found below 50 to 60 m in Lake Tahoe (Abbott et al. 1984). Based on sediment trap data for Lake Tahoe (Heyvaert 1999), Jassby et al. hypothesized that it is the combination of phytoplankton and inorganic particulate matter that accumulate at intermediate depths which is mixed into the surface waters and results in the December minimum in clarity.

Seasonal and trend analysis of the transparency data using advanced statistical treatment revealed a strong change in the seasonal effects over the 29-year record. In the late 1960s and early 1970s, the seasonal pattern was essentially unimodal with a midwinter maximum, usually in February and a late spring-early summer minimum, usually in June. By the mid-1970s, a late fall-early winter secondary minimum, usually in December, gradually began to develop. This pattern has continued to the present strong bimodal pattern of December and June minima (Figure 4-31). Another feature of the time course is a long-term decline in the seasonal amplitude, i.e., less variation between seasonal high and low values in recent years.

Interannual Variability

PCA provides an understanding of the longer-term variability of Secchi depth. Two modes were found to be significant, each exhibiting a decadal-scale trend as well as a year-to-year variability around this trend. One was observed during the weakly stratified autumn-winter period and the other during the more stratified spring-summer period. Mode 1 represents the autumn-winter period of weak or no thermal stratification, during which the thermocline erodes and mixing occurs; as discussed above, the depth of mixing is variable and not always complete. Mixing depth has a significant influence on the year-to-year variability around the trend line but not in the same manner in which it controlled primary productivity. The coefficient for mixing depth is positive, implying that deeper mixing results in higher Secchi measurements. Once the depth of mixing exceeds an intermediate depth (approximate depth range for the deep chlorophyll maximum and other suspended particulate matter), deeper mixing brings up waters with less particulate matter. The effect of deep mixing is best understood as a dilution of light-attenuating particles, be they phytoplankton or inorganic sediment.

Mode 2 represents variability around the trend line during the spring-summer when the lake is more strongly stratified. As observed for the seasonal minimum at this time, the interannual variability in stream discharge causes the year-to-year difference in clarity at this time. Blackwood Creek spring streamflow as an index of sediment discharge gave a very good prediction of the interannual variability seen in Mode 2. Blackwood Creek was used because it has a continuous database extending back prior to 1970 and because of its proximity

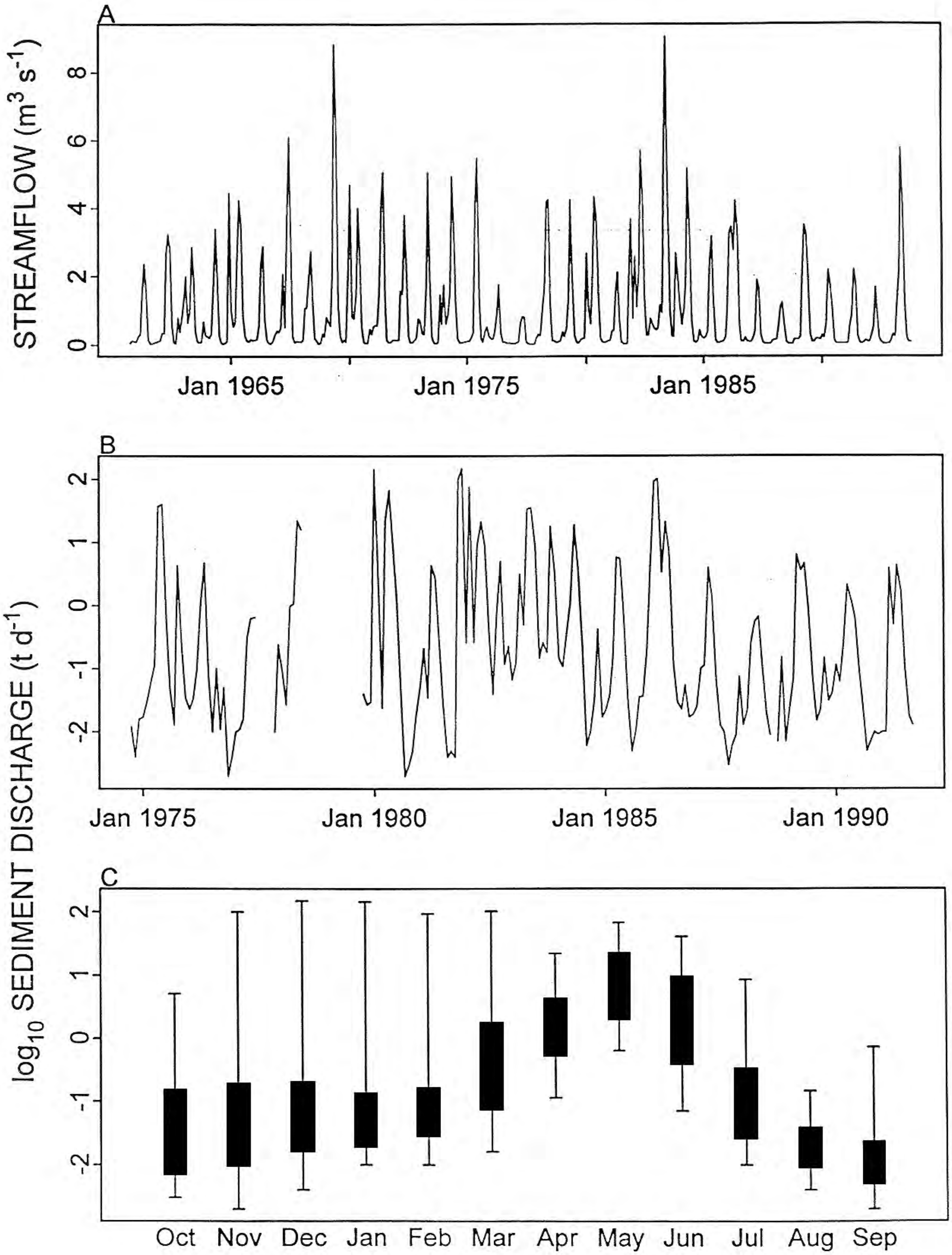


Figure 4-30—Seasonal decline in clarity during May and June related to sediment discharge from inflowing tributaries (from Jassby et al. 1999).

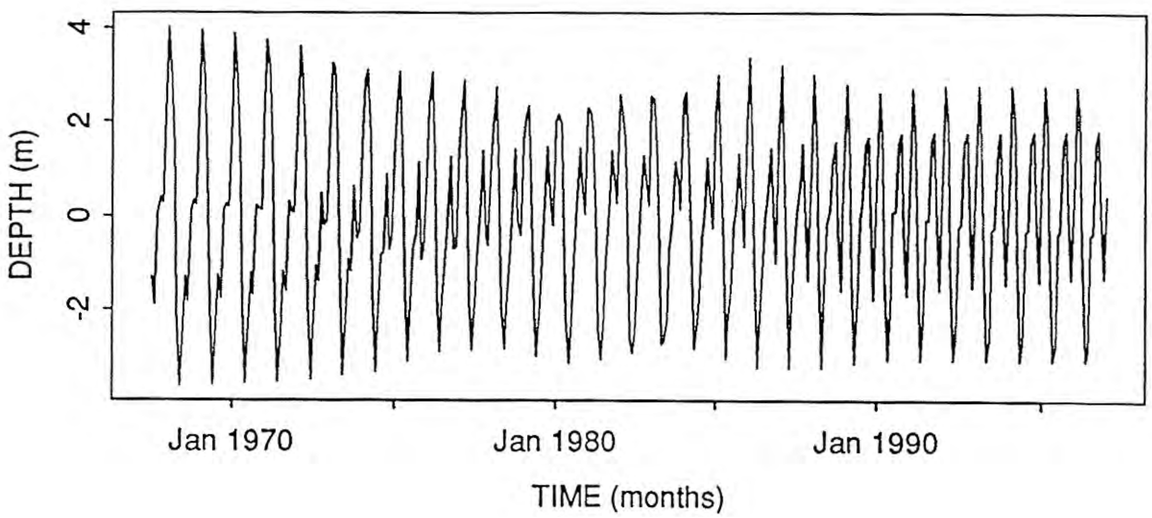


Figure 4-31—Development of bimodal pattern of clarity with the onset and intensification of a secondary minimum, usually in December (from Jassby et al. 1999).

to the index station where the long-term Secchi measurements are made.

Compression of Euphotic Zone

Goldman (1988) emphasized that from 1979 to 1986 there was a trend toward a reduction in the depth of the euphotic zone with the average depth of maximum photosynthesis moving closer to the surface. Long-term monitoring of lake in vivo fluorescence or chlorophyll shows a prominent peak in algal biomass at a depth of 50 to 90 meters. This peak is significantly below the typical Secchi depth of 20 to 25 meters and therefore has no direct influence on the documented decline in clarity, as measured by Secchi disk. This deep chlorophyll maximum can be anywhere from three to 10 times more concentrated than in the water between the surface and the Secchi depth. If decreasing clarity causes a rise in the deep chlorophyll maximum, this could result in a dramatic acceleration of the decrease in clarity in the surface waters, which would be significantly more dramatic than the steady decline that has been observed to date. Given the thickness of the deep chlorophyll layer (approximately 60 meters) and its elevated mean concentration, the amount of algae in this region is on the order of at least ten times higher than that in the waters down to the Secchi depth. Obviously, changes in the location of this layer have potentially dramatic consequences for lake water quality. A compression in the euphotic zone also would effect the distribution of submerged aquatic plants, which are important to the life history of the lake trout population in Lake Tahoe.

What has been the pattern of algal response to nutrient additions? Should management focus on reduction of a single nutrient?

The response of Lake Tahoe water to nitrogen and phosphorus enrichment has been tested using algal bioassays since the 1960s. Goldman et al. (1993) presented a 25-year record of bioassays conducted at Lake Tahoe showing that a decadal scale transition from N and P colimitation to primarily P limitation occurred around 1980. They also examined interannual and seasonal scales of macronutrient (N and P) limitation. Recent work done by Hatch et al. (in press) using algal bioassays has provided information on the fraction of TP in stream inflow, which is readily biologically available to lake phytoplankton.

Algal bioassays are experiments in which small amounts of nutrients or other chemicals are added to algae under controlled conditions, with the change in growth directly measured. The bioassays most commonly done at Tahoe since the 1960s have been over three to seven days in duration and utilize the natural phytoplankton community. These assemblages, obtained directly from the lake, are used because they are adapted to the nutrient supply conditions in the lake and include the naturally diverse composition of algal species (which also may have differing nutritional needs). Enrichment bioassays provide an indication of nutrient limitation. A nutrient is said to be "limiting" when it is in shortest supply relative to phytoplankton needs, and therefore its abundance controls the growth of the organism. In extrapolating the bioassay results to the lake as a whole, the fact must be considered that these small-scale bioassays eliminate many important nutrient fluxes and alter the physical, chemical, and biological environment. However, because the euphotic zone of Lake Tahoe is not significantly influenced by nutrient processing in the bottom sediments, because the residence time for nutrients can be on the order of decades, and because top-down or biological processes do not appear to regulate algal biomass, the results of these bioassays are considered to be highly relevant. The long record of bioassays gathered from Lake Tahoe using a consistent method has proved extremely useful for evaluating long-term changes. When combined with lake chemistry data and information on atmospheric and watershed nutrient loading ratios, these simple enrichment bioassays have provided valuable complementary evidence on the temporal dynamics of nutrient limitation in the lake.

Long-term Shift in Bioassay Response

In a typical bioassay, lake water is collected from the upper photic zone (0 to 40 m), prefiltered through 80-μm mesh netting to remove the larger zooplankton, and returned to the lab. The water is distributed among experimental flasks to which small amounts of N (20 μg N/L) or P (10 μg P/L) or the combination of both are added. One set of flasks is left as a control, and all treatments are triplicated. The flasks then are placed in a laboratory incubator under fluorescent lighting at ambient lake temperature and daylength, and growth response of phytoplankton is measured over a period ranging from three to seven days. Relative growth is assessed by measuring carbon 14 (^{14}C) accumulated in phytoplankton during growth, or by measuring changes in algal biomass (i.e. fluorescence or chlorophyll *a*). Treatments are stimulatory if the mean growth response exceeds the control at the $p=0.05$ level of significance.

Goldman et al. (1993) examined the long-term set of 110 bioassays (1967-1992), that tested response to either N or P additions alone, for the presence of trends on the decadal scale. The most outstanding feature of this record is a long-term shift from colimitation by both N and P to predominant P limitation. In earlier tests (1967-1981), growth stimulation was observed in about 45 percent of the N bioassays and in about 25 percent of the P bioassays. In later tests (1982-1992), P stimulation was observed more frequently (nearly 90 percent of the P bioassays), while N stimulation was rare (occurring in six percent of the N bioassays) (Table 4-5). The exact timing of the shift is difficult to discern, but it was concluded to have occurred in the late 1970s or early 1980s.

Other data also suggest that the nature of nutrient limitation had changed in Lake Tahoe. Chang et al. (1992) combined field measurements of lake chemical and biological indicators with single-species bioassays during 1988 and 1989. Their results suggested that phosphate was limiting algal biomass during that period. Hunter et al. (1990) described an increasing abundance of the chrysophytes *Dinobryon*, *Kephyrion*, *Synura*, and *Uroglena* in Lake Tahoe phytoplankton during the 1980s and argued that the species changes indicated higher ratios of available N:P. Marjanovic (1989) collected sedimenting material in traps suspended at several depths in Lake Tahoe; in the shallowest traps (140m) from June 1 through August 31, 1988, (approximately the period of highest productivity) material had an N:P (molar) ratio of 70, indicating extreme P deficiency (Healey and Hendzel 1979). No particulate N:P data exist for the earlier period, but Holm-Hansen et al. (1976) reported a particulate C:N (molar) ratio of 19 in the mixed layer at the end of the bloom in August, symptomatic of extreme N deficiency (Healey and Hendzel 1979).

Table 4-5—Summary of long-term change in nutrient limitation in Lake Tahoe to a phosphorus stimulated system (from Goldman et al. 1993).

	Not Stimulatory	Stimulatory	Total
	NO_3 bioassays		
1967-81	16	12	28
1982-92	29	2	31
Total	45	14	69
	PO_4^3 bioassays		
1967-81	14	5	19
1982-92	4	28	32
Total	18	33	51

Jassby et al. (1994) hypothesized that the shift from N and P colimitation to predominant P limitation is due to a slow, decadal change in the relative sizes of lake N and P reservoirs fueled by atmospheric deposition.

Interannual and Seasonal Changes in Bioassay Response

Goldman et al. (1993) examined the bioassay record for year-to-year variability. To avoid the confounding effects of long-term shifting nutrient limitation, these authors focused on the period from 1982 to 1992, in which P enrichment was consistently stimulatory. The magnitude of P response (expressed as percent of control response) was compared for bioassays done in, or close to, July each year. The magnitude of P response fluctuated from year to year and ranged from 199 percent in 1985 to 108 percent in 1990 . To see whether the fluctuations in magnitude of P response were related to spring mixing depth, Goldman et al. (1993) compared July bioassays, which had similar duration (six days), with spring mixing depths for the corresponding year. A significant positive association was found between depth of spring mixing and magnitude of P response, i.e., deeper mixing resulted in a more positive P response. Adding N and P together typically resulted in the largest response, as well as the highest interannual variability in response. In general, the largest source of interannual variability identified for Lake Tahoe is the depth of spring mixing (Goldman et al. 1989). Deeper mixing results in an increased upwelling of regenerated nutrients from the lake depths and a higher annual primary productivity.

Goldman et al. (1993) also looked at seasonal variation in responses. Because the number of bioassays was limited each year, their comparison focused on the highly stratified period (July through September) and the remainder of the year, which was either weakly stratified or non-stratified. The significance of bioassay response was independent of the seasonal period for both N and P; that is, N or P stimulation was not associated with either the highly stratified period or the remainder of the year. This lack of seasonal effect on the significance of bioassay response is an important observation. It supports assessment of the long-term shift without taking into account a possible confounding effect of season.

The authors also examined the effect of season on the magnitude of bioassay response. To minimize confounding factors they focused on the period beginning in 1982 when P stimulation, and lack of N stimulation was a consistent feature of the bioassays. The highest magnitude of responses (greatest stimulation relative to the control treatment) tended to occur during stratification. Two potential causes for the increased summer response were forwarded. First, incubation under summer conditions of higher temperatures and longer daily light cycles may have resulted in a faster growth rate in the summer bioassays, and thereby may have affected the magnitude of response. Alternatively, changes in the ratio of available N:P between the two periods could underlie the seasonal differences much as for the interannual differences.

Contribution of Nutrient Loading to Changes in Lake Response

Jassby et al. (1994) analyzed atmospheric and tributary N and P loading data to assess their roles in the shifting lake response to nutrients. They found that the N:P (atomic) ratio in atmospheric loading was well above the "Redfield ratio" of 16N:1P and much more likely to favor P than N limitation (Flett et al. 1980; Levine 1983). In tributary loading, the N:P ratio was less than 16 and more likely to favor N limitation. For 1989 to 1991, atmospheric and tributary loading combined had a dissolved inorganic-N to soluble reactive-P (DIN:SRP) ratio of 33 and a total-N to total-P (TN:TP) ratio of 26; the effect of atmospheric deposition on the ratio overwhelmed that of runoff, and total loading favored P limitation. These loading data are consistent with the persistent P limitation observed from 1982 to 1992 and indicate a potentially strong influence of atmospheric deposition on nutrient limitation.

Jassby et al. (1994) hypothesized that the shift from N and P colimitation to predominant P limitation is due to a slow decadal change in the relative sizes of lake N and P reservoirs fueled by atmospheric deposition. When Jassby et al. (1995) examined the consistency of this hypothesis with lake water chemistry data collected since the mid-1970s, they found the monthly time series for lake NO_3^- and THP data only weakly reflected long-term changes in phytoplankton activity. This was not unexpected, given the masking effect of large interannual variability caused by spring mixing and the nearness of expected changes to analytical limits of detection. However, when they assessed loading rates and pools of nutrients in the lake, they found that the time scale necessary for change in the size of nutrient pools was of sufficient magnitude to account for the shifts in nutrient limitation. Significant changes in the N:P ratio over a period of several decades are quite conceivable, and shifting nutrient limitation accordingly can be attributed to loading. Atmospheric deposition is essential to account for the observations. In the absence of atmospheric sources, the TN:TP ratio can be shown to slowly move toward N limitation, with a "halving" time of at least 150 years.

Although P limitation was more common than N limitation in nutrient enrichment bioassays conducted from 1980 to 1992, Jassby et al. (1995) indicated that the conditions in the lake at this time, probably favor P limitation only marginally. For example, the mean annual TN:TP ratio in the photic zone was 25 ± 0 for 1992 to 1993. In comparison, Downing and McCauley (1992) found that N limitation was significantly more frequent in lakes with ratios less than 31. Although values from such comparative cross-sectional studies must be applied with caution to individual lakes, their study does suggest that Lake Tahoe may still be close to the boundary separating predominantly N from predominantly P limitation. Some lakes are so closely in balance that adding N and P simultaneously is required to obtain any stimulation of primary productivity (Blomqvist et al. 1989). Presumably, small changes in the N and P balances due to, for example, a change in zooplankton composition (Peinert et al. 1989) or denitrification rate (Levine and Schindler 1992) or other causes could induce a reversal in nutrient limitation. Although recent bioassay data (1992-1998) and the long-term data set have not yet been completely analyzed, brief inspection indicates that N and P colimitation has been observed in several of the bioassays since 1992 (TRG, unpublished). This seems to support the idea that N and P are closely in balance. No evidence exists, however, that the 1980s shift at Lake Tahoe is in fact due to causes other than the cumulative effect of loading. The above analysis indicates that, in the absence of loading changes, the TN:TP ratio should continue to increase, with N limitation even less frequent. This is especially true given the overwhelming and continued importance of atmospheric deposition to the nitrogen budget.

Relative Importance of Stream-borne Phosphorus to Lake Tahoe Phytoplankton

Lake Tahoe basin streams contribute a significant portion of the P loading to the lake. This TP is contributed as dissolved and particulate forms of inorganic and organic phosphorus; however, not all of this P is readily biologically available to lake phytoplankton, that is, it is not readily taken up for use in metabolism, primary production, or storage by the phytoplankton. While, dissolved inorganic P (PO_4^{-3}) is generally considered to be immediately bioavailable to phytoplankton, only a portion of the DOP is thought to be readily bioavailable, and the bioavailability of PP is quite variable among aquatic systems. To better assess the importance of stream TP for lake phytoplankton growth, the bioavailability of P needs to be assessed.

Hatch et al. (in press) performed a series of bioassays during the spring runoff period and summer of 1996 to characterize the short-term (six days or fewer) bioavailability of stream P from seven basin tributaries. The lake phytoplankton response to different percentage additions of stream water in lake water (ranging from one percent to 10 percent) was tested, as well as the response to 0.45 μ-filtered, 63 μ-filtered, and unfiltered tributary water. The latter bioassays were done to determine the proportion of the phytoplankton response attributable to soluble and particulate fractions in the tributary water.

These authors found dissolved inorganic P best represented Lake Tahoe short-term stream bioavailable P, while particulates (>0.45 μm) did not contribute much short-term bioavailable P. Because the lake was predominantly P-limited during the study, with algae showing only slightly higher growth response to N and P added in combination than to P alone, much of the bioassay growth responses could be attributed to biologically available P in the tributary water. Hatch et al. found all the tributary waters to stimulate algal growth, with increased response associated with higher percentage additions of stream water. Approximately 75 to 90 percent of bioassay response was found to be due to nutrients in the less than 0.45-μm (dissolved) fraction of the tributary water (Figure 4-32). PO_4^{-3}, and to a lesser extent DOP concentrations in the tributary water, was significantly correlated with bioassay responses, while particulate-associated P fractions were not significantly correlated with bioassay response.

The study indicated that PO_4^{-3} is the fraction of TP loading from streams, which is readily available to phytoplankton in the short term. Hatch (1997) estimated that PO_4^{-3} composed about six to 19 percent of the annual TP concentrations for Lake Tahoe tributaries from 1989 to 1996. Approximately 75 percent of the annual stream $PO4^{-3}$ loads occur during the spring runoff (Hatch 1997). Thus a significant "pulse" of available P as PO_4^{-3} enters with the spring runoff to help fuel spring and summer primary production. DOP also showed a weak correlation to bioassay response, indicating that it also may contribute some readily bioavailable P. However, only a portion of the DOP is likely to be readily bioavailable (Sonzogni et al. 1982). In addition, it seems likely that only a relatively small portion of the DOP is short-term bioavailable P in Tahoe, based on DOP and PO_4^{-3} concentrations in the stream treatments and bioassay responses in Hatch et al. (in press), however, additional work is needed to confirm this. Hatch estimated DOP to range from six to 42 percent of the annual TP concentrations for Lake Tahoe tributaries from 1989 to 1996. Note that Holm-Hansen et al. (1976) also provided evidence that a portion of the DOP is utilized in Lake Tahoe. He found that much of the DOP between 5 and 100 m in Lake Tahoe had been depleted, suggesting that hydrolysis of DOP compounds by algal phosphatases may provide a source of PO_4^{-3} to phytoplankton in the photic zone.

Hatch et al. (in press) indicate that much of the particulate P contributed by tributaries is not likely bioavailable in the short term. This is significant because particulate phosphorus is a significant fraction (45 to 88 percent) of annual TP concentrations in Tahoe tributaries (Hatch 1997). While much of this PP may not be available for uptake on the scale of six days, it may become available over longer time scales, for example, weeks to months. They found that 23 to 80 percent of the PP in stream samples tested was in the silt- and clay-sized fraction. These small size fractions with associated P may remain in suspension in the photic zone for extended periods of time, increasing their potential for bioavailability over longer time spans. Therefore, while dissolved P is most important to algal

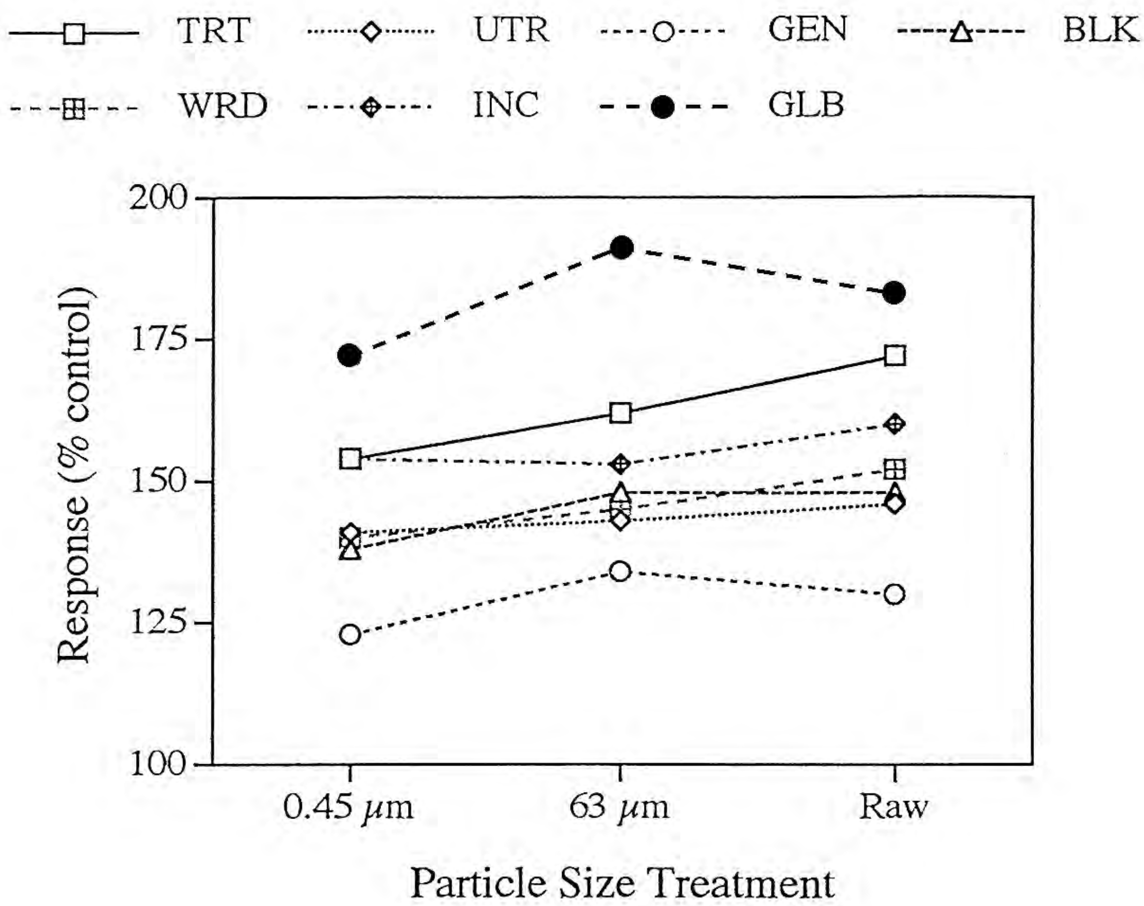


Figure 4-32—Impact of material size class from Lake Tahoe tributaries on lake phytoplankton growth using standard TRG bioassay techniques. The 0.45 μm treatment corresponds to the dissolved fraction; the 63 μm treatment includes all dissolved materials and small particulate matter including silt and clay; the raw treatment includes all dissolved and particulate fractions.

response over the short term, fine particulate-suspended P may add to the bioavailable P over time. However, PP in the sand-sized range will settle relatively rapidly out of the water column in Lake Tahoe and may be removed from potential phytoplankton availability through burial. Additional study of BAP dynamics in the lake is needed.

Limitation by Trace Metals

Iron also may be a contributing factor to algae growth (Goldman and Carter 1965). Several studies have found iron (Iron) to be a limiting factor in some areas of the lake. In their studies, Iron addition increased biological carbon uptake by up to 40 percent. As with phosphorus loading, Iron loading is commonly associated with erosion and sediment transport. Because most Iron loading occurs in particulate form, it is generally considered unavailable for biological uptake. However, mineralization is presumed to make the nutrients available at some point (Elder et al. 1976).

Single Nutrient Versus Multiple Nutrient Control

Reversing the ongoing eutrophication of Lake Tahoe in part depends on reducing the nutrient availability. This is most feasible by controlling sources of nutrients to the lake. Both N and P have been limiting during the past 30 years, with N and P colimitation more prevalent before the early 1980s, and P limitation predominant from the early 1980s to the early 1990s. Given the current knowledge of nutrient limitation in Lake Tahoe, the most effective strategy for controlling algal growth should be determined.

One strategy is to focus on P control to reduce algal growth under the current condition of predominantly P limitation. P limitation has been more prevalent in recent years, and continued atmospheric deposition of N will most likely drive the lake toward stronger P limitation. Successfully reducing available P by control measures would further increase the N:P ratio. The degree to which atmospheric N loading can be controlled is an important consideration in evaluating this strategy. If it is found that little change in atmospheric N loading can be expected as a result of control efforts, or if N control is otherwise not feasible, the lake N:P ratio will continue to increase, making P control the most effective control strategy.

An alternative strategy would be to focus only on N control. Under conditions of predominant N limitation or N and P colimitation this strategy could be effective. However, the greatest contribution of N loading to the lake is from atmospheric deposition; therefore, controlling N deposition is an extremely important component of a strategy that emphasizes N. As indicated above, information is needed on the extent to which atmospheric deposition of N onto the lake can be controlled. Under conditions of prevalent P limitation, P control would still be necessary.

A case can be made for multiple nutrient control. As mentioned above conditions in the lake probably favor P limitation only marginally. It is conceivable that the lake could undergo a shift back to colimitation as a result of small changes in the N and P balances. Combined N and P control measures may be expected to alter loading; however, the net effect of these changes on lake N:P ratios and nutrient limitation is uncertain. Given the current close balance between N and P and the uncertainty about future nutrient limitation under changing loading conditions, it may not be prudent to discount N control altogether. According to the nutrient budget presented above, 56 percent of the total-N loading to Lake Tahoe comes directly from atmospheric deposition and is related to air quality. On the other hand, 73 percent of the TP entering the lake is derived from the watershed. While a management plan for P control would include such actions as erosion control, revegetation, and purchase of sensitive lands, an N-control strategy must consider both in-basin and out-of-basin sources, such as automobile exhaust and agrochemical residues. N control could be difficult to implement, especially if out-of-basin sources are dominant. Given the current conditions of P limitation in Lake Tahoe and the lack of unambiguous data on sources of atmospheric N, restoration projects that emphasize P control should be a priority at this time. Should continued research on air quality and lake response present a strong case for a need for simultaneous N control, this strategy would require renewed evaluation.

Do the existing long-term data for other biological chemical or physical characteristics of Lake Tahoe show significant trends for other parameters besides algal growth, clarity, and nutrients?

Dissolved oxygen (DO) is one of the most important features of lake water quality. When this critical constituent is too low, a number of beneficial uses of a waterbody are lost. This results from a reduction of habitat available to fish, increased stress to fish and other macrobiota, change in aquatic biodiversity toward more undesirable species, water taste and odor problems, and enhanced released of nutrients from the bottom sediments. DO concentrations should be greater than 6 mg/L to maintain a health salmonid community.

The vertical profile of DO in lakes is largely determined by mixing processes, thermal stratification, and biochemical oxygen demand (BCOD). Typically, the higher the levels of organic matter in the water the higher the oxygen demand and the lower the oxygen concentrations. As bacteria decompose organic matter (including dead phytoplankton), the water's oxygen is consumed. In the mixed layer, the loss of oxygen is often not significant because of reaeration from the atmosphere and photosynthesis by algae. In general, the deeper portions of lakes will experience the most severe oxygen depletion because BCOD occurs both in the water and at the bottom sediment (sediment oxygen demand or SOD); also, when the lake is stratified or if mixing is not complete to the bottom, reaeration does not occur.

While DO in lakes exhibits distinct daily, seasonal, annual, and interannual patterns, in Lake Tahoe long-term or decadal scale changes are of greatest concern. Specifically, there is a concern that the organic matter produced as algal primary productivity increases is creating a higher BCOD with a concomitant decline in DO. Even if the resulting DO exceeds the recommended 6.0 mg/L value for a coldwater fishery, any progressive decline in the oxygen content of Lake Tahoe is significant because restoring a lake's DO is very difficult, even in smaller and much more manageable waterbodies.

DO concentrations in the deepest portion of a lake largely reflect SOD and provide early insight into changing conditions. As part of the lake's routine monitoring, complete vertical profiles of DO over one of the deepest portions of the lake are made (TRG, unpublished). Monthly measurements are made from the surface to a depth of 450 meters throughout the year. Since 1984, DO concentrations at this depth have been made on over 175 occasions.

A plot of the measurements shows a considerable amount of variation around the line of linear best fit for DO at 450 m (Figure 4-33). The range of values is 6.9 to 11.3 mg/L, with an overall mean of 9.05 mg/L; the median value was 9.0 mg/L (i.e., 50 percent of the concentrations were both above and below this value). Within this range, the values have a normal distribution. For comparison, the range of DO concentrations at 400 m was similar, albeit the normal distribution shifted toward higher values. Both the mean and median at this relatively shallower depth were identical at 9.2 mg/L with a range of 7.1 to 11.4 mg/L. This increase in DO away from the bottom is expected because the direct influence of SOD diminishes. Despite the observed variation when the entire database is considered (partially due to seasonal patterns), there appears to be a downward trend over the 15-year period of record from greater than 9.0 mg/L to less than 9.0 mg/L.

Reducing these data by calculating annual mean values allows a closer evaluation of this decline in DO (Figure 4-34). The linear best fit model shows that DO has fallen by 0.66 mg/L from approximately 9.41 mg/L in 1984 to 8.75 mg/L in 1998. While there still is some variation around the line of best fit, the time variable (i.e., passage of years) explains 45 percent of the observed decrease. Given the well-known link between algal production and loss of DO in lakes and given the long-term increase in primary productivity in Lake Tahoe, the long-term changes in these two parameters are likely related.

Without complete mixing each year, it is valid to question whether the observed decline in annual average DO was related to incomplete mixing and therefore a reduction of reaeration. Years of complete mixing from 1984 to 1998 included 1985, 1989, 1993, 1997, and 1998. Only in 1998 was the annual average DO higher than expected, suggesting no significant impact of deep mixing on the yearly mean value. The higher DO observed in 1998 appears due to increased values during the summer and fall. While an upward trend might be inferred from the 1995 to 1998 segment of the database, primary productivity and Secchi depth data suggest that interpreting temporally truncated portions of the long-term data can lead to erroneous conclusions. Continued monitoring will help clarify this issue.

Analysis of the 450 m DO data by month shows the expected seasonal pattern (Figure 4-35). Regardless of the maximum mixing depth, turnover in Lake Tahoe occurs from February to April, and by May it is complete. From May to September, DO at 450 m remains relatively uniform, between 9.0 and 9.5 mg/L. From September to October, concentrations begin to decline due to increased SOD and presumably because phytoplankton produced in the surface waters during the spring-summer period settle into the deeper waters and decompose. This consumption of DO continues through January when the seasonal minima are observed. The increase between January and March is coincident with turnover and reaeration of the deeper waters.

Because January is the month where minimum DO is measured at depth, it is

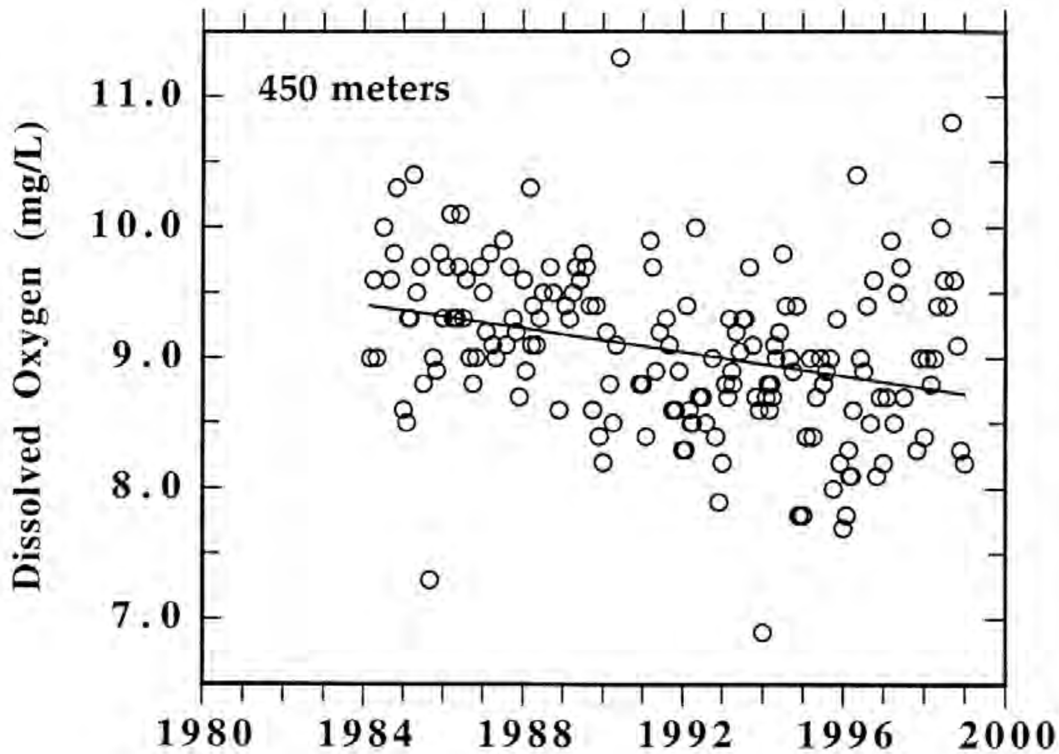


Figure 4-33—Individual measurements of dissolved oxygen at a depth of 450 m below the surface in Lake Tahoe since 1984.

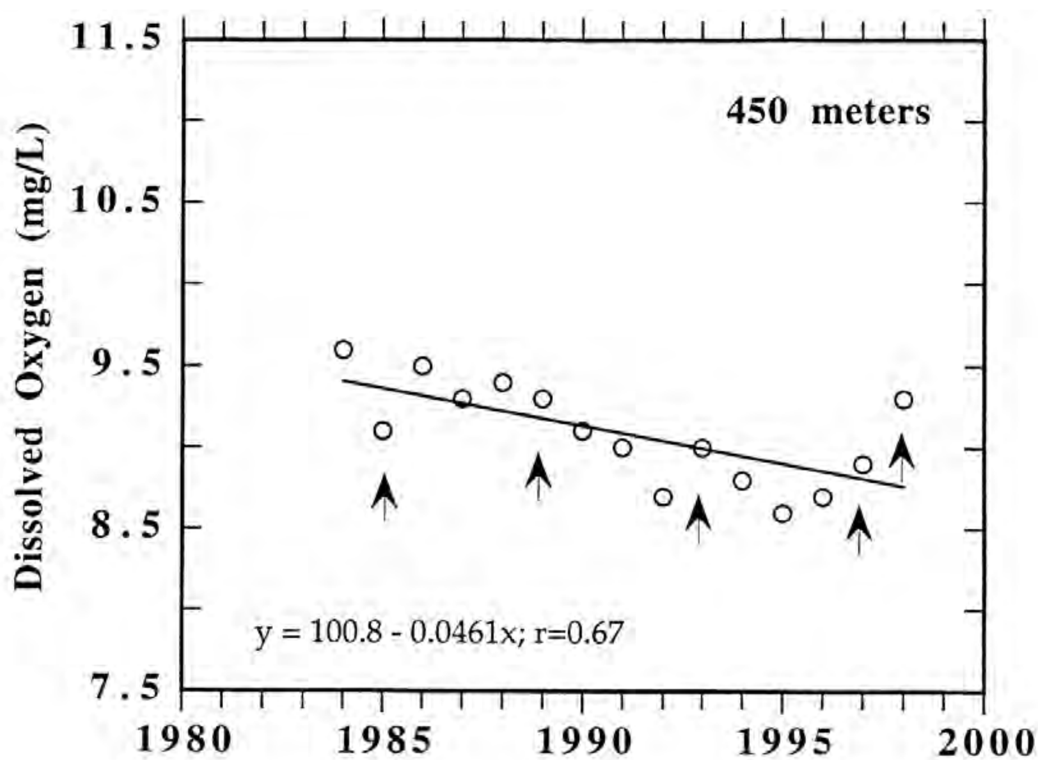


Figure 4-34—Decline in annual average dissolved oxygen at 450 m. Arrows represent years of complete mixing.

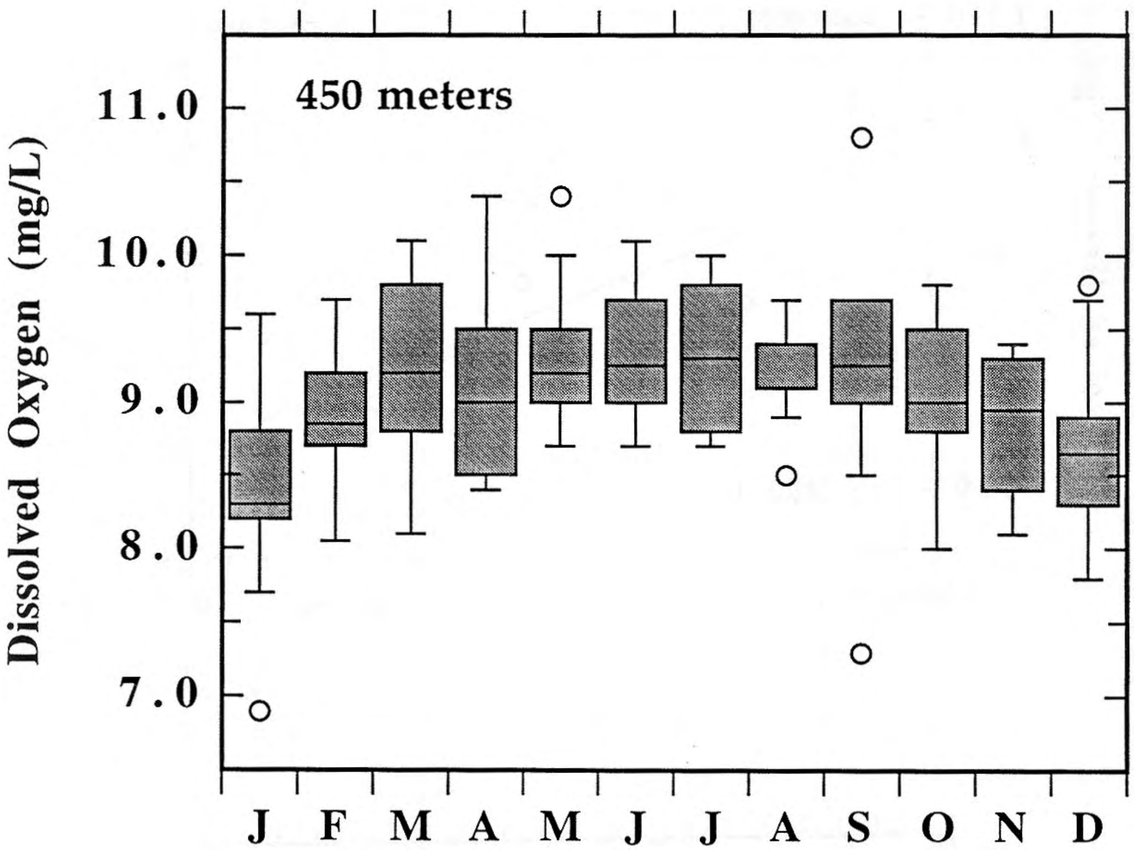


Figure 4-35—Mean monthly values for dissolved oxygen at 450 m, showing the gradual decline in concentration throughout the fall and early winter until mixing during February and March. Solid line in box represents median value. Box ranges from 25th to 75th percentiles, and lines denote maximum and minimum values. Circles are outlying values.

instructive to evaluate the long-term change at this location. The decline in lake DO during January at 450 m is even more pronounced that the change in annual average DO (Figure 4-36). Based on the statistical line of best fit, DO declined by 1.6 mg/L from 9.3 mg/L in 1984 to 7.7 mg/L in 1998 (again, note that specific years may vary from the line of best fit). This represents a 17 percent decline. At this rate, DO at 450 m in January will decline to 6.0 mg/L in slightly more than 10 years (2012). Similarly, if the present rate of decline continues, the average DO concentration for the entire year at 450 m will dip below 6.0 mg/L in 2058.

The observed change to this fundamental indicator is disturbing. Not only is dissolved oxygen critical to maintain fish habitat, an aerobic condition at the sediment-water interface results in the formation of a chemical barrier that largely prevents the migration of phosphorus from the sediments and into the water column. Should dissolved oxygen decline to zero at the bottom, this barrier will break down, resulting in the auto-catalytic release of very large quantities of P to Lake Tahoe. Deep-water dissolved oxygen concentrations should be considered as a water quality Threshold for Lake Tahoe. Formal presentation of a recommended value is premature at this time; however, efforts are underway to make this determination.

Phytoplankton Species Composition

Phytoplankton Response to Ecosystem Changes—Phytoplankton communities are central to many of the environmental issues at Lake Tahoe. Algae are the primary producers, the base of the aquatic food

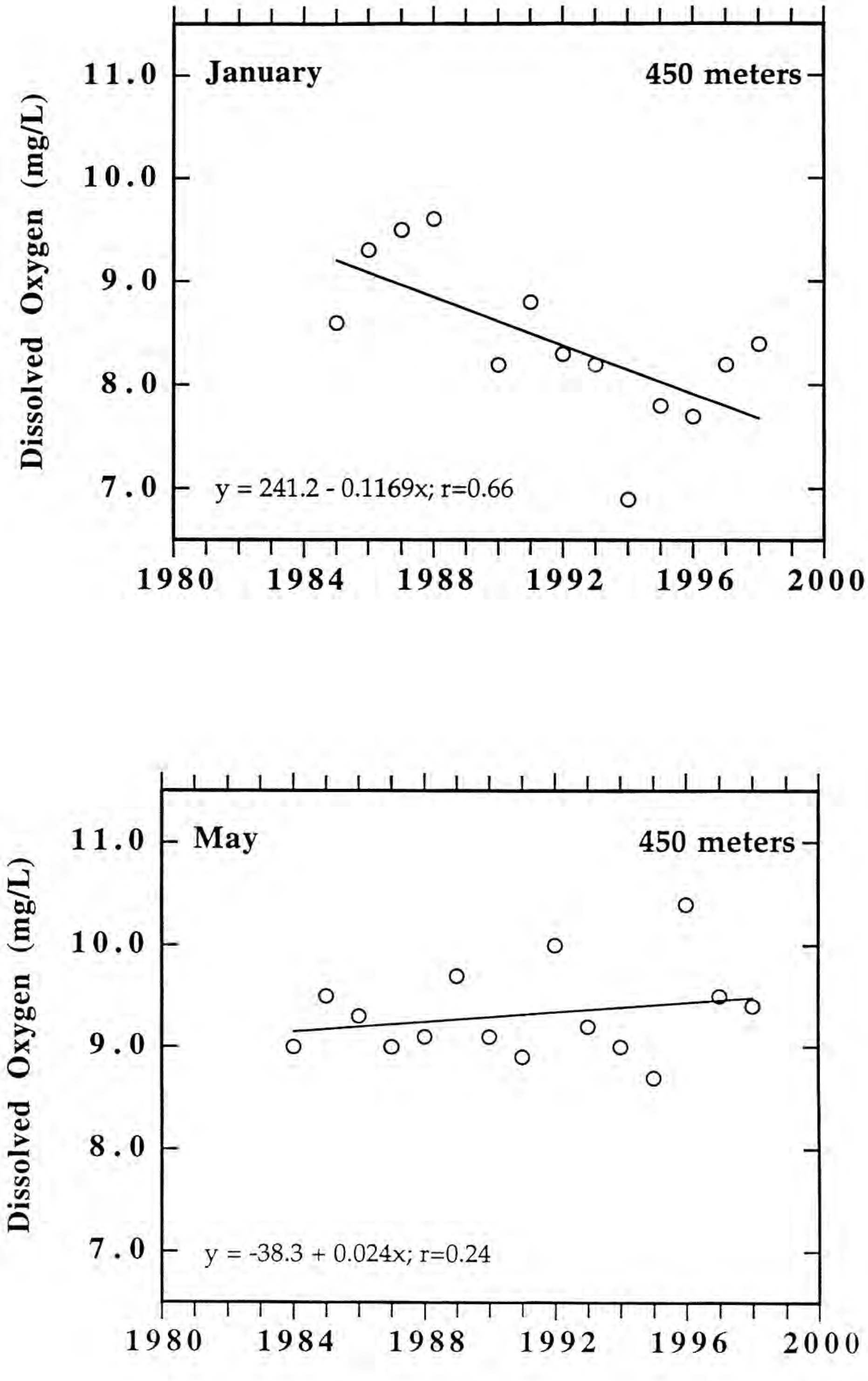


Figure 4-36—Pronounced decline in dissolved oxygen in January prior to lake mixing.

web. Blooms of certain species also can result in taste and odor problems in domestic water supplies. Phytoplankton is very responsive to physical and chemical changes in the aquatic environment. This rapid biological response can be advantageous where managers and scientists have a good understanding of algal community dynamics. Changes observed in the algal community then can be used for predictive purposes and can inform management decisions.

Phytoplankton community changes will directly affect higher trophic levels of the food web. When the algae respond to the fluctuating physical and chemical environment, these changes will affect food quantity and quality. Algal response also will strongly affect lake clarity. Increases in phytoplankton abundance and biomass will increase the overall number of particles in the water column. Light will penetrate to shallower depths because of increasing light scattering and absorption. As a consequence, the eutrophic zone becomes compressed (Goldman 1988; Kirk 1994).

Phytoplankton as Ecosystem Indicators—A useful bio-indicator responds to ecosystem perturbations. The response should be definitive and relatively rapid. Phytoplankton fit these criteria. The algae are easy to sample and easy to assay. Almost 30 years of continuous collections are available for Lake Tahoe from all depths in the euphotic zone. In the last decade, the phytoplankton samples have not been assayed; however, data from the previous two decades suggest that phytoplankton communities are predictable. Changes have occurred in the algal community as a result of changing conditions in the lake (Vincent 1978; Hunter et al. 1990).

Historically, efforts have been made to link the presence and quantity of individual algal species to changing trophic conditions in Lake Tahoe (Byron and Eloranta 1984; Goldman 1988). However, the use of only one or two algal species to prove the case of eutrophication has been unreliable. Individual taxa have varying responses to changing environmental conditions. In addition, there exists an incomplete understanding of what parameters trigger growth changes in individual species.

Even when whole groups of phytoplankton, such as diatoms, are considered, the link to eutrophication has not been dependable. Stockner (1971), working with diatom assemblages, reported that increases in araphid pennate diatoms or decreases in centric diatoms were an indication of increased eutrophication. Similarly, analysis of sediment cores from Lake Tahoe has shown that in the recent past (since 1960) the araphid pennates have increased in abundance in the phytoplankton community, possibly to the exclusion of some centric diatoms (Byron and Eloranta 1984). Nevertheless, these authors and other investigators have cautioned against the use of the ratio of araphid pennates to centrics (A/C) as a sole indicator of eutrophication (Brugam 1979).

While the A/C ratio may not be a valid indicator of eutrophication, the approach of considering changes within the entire community of phytoplankton, rather than individual species, seems to be the most valuable measure of ecosystem change (Reynolds 1980). Indeed, for Lake Tahoe, the phytoplankton community has shifted from diatom dominance to a shared dominance among diatoms, chrysophytes, and cryptophytes (Hunter et al. 1990) (Figure 4-37). Individual species have appeared and disappeared within the phytoplankton, and species diversity has increased. These indications are very reflective of the physical and chemical changes that have occurred in the lake over the same period.

For a large deep lake, like Lake Tahoe, such physical factors as depth of mixing, weather patterns, and surface inputs play an important role in determining the phytoplankton growth response (Goldman 1988). The longevity of the physical perturbations and the ensuing nutrient availability will determine which phytoplankton taxa in the community will dominate. The species whose growth requirements fit best to the current physiological characteristics and ecological conditions will respond with increased growth (Reynolds 1980).

Phytoplankton species respond to seasonal cues with predictable temporal patterns. Often it is not possible to predict algal community dominants

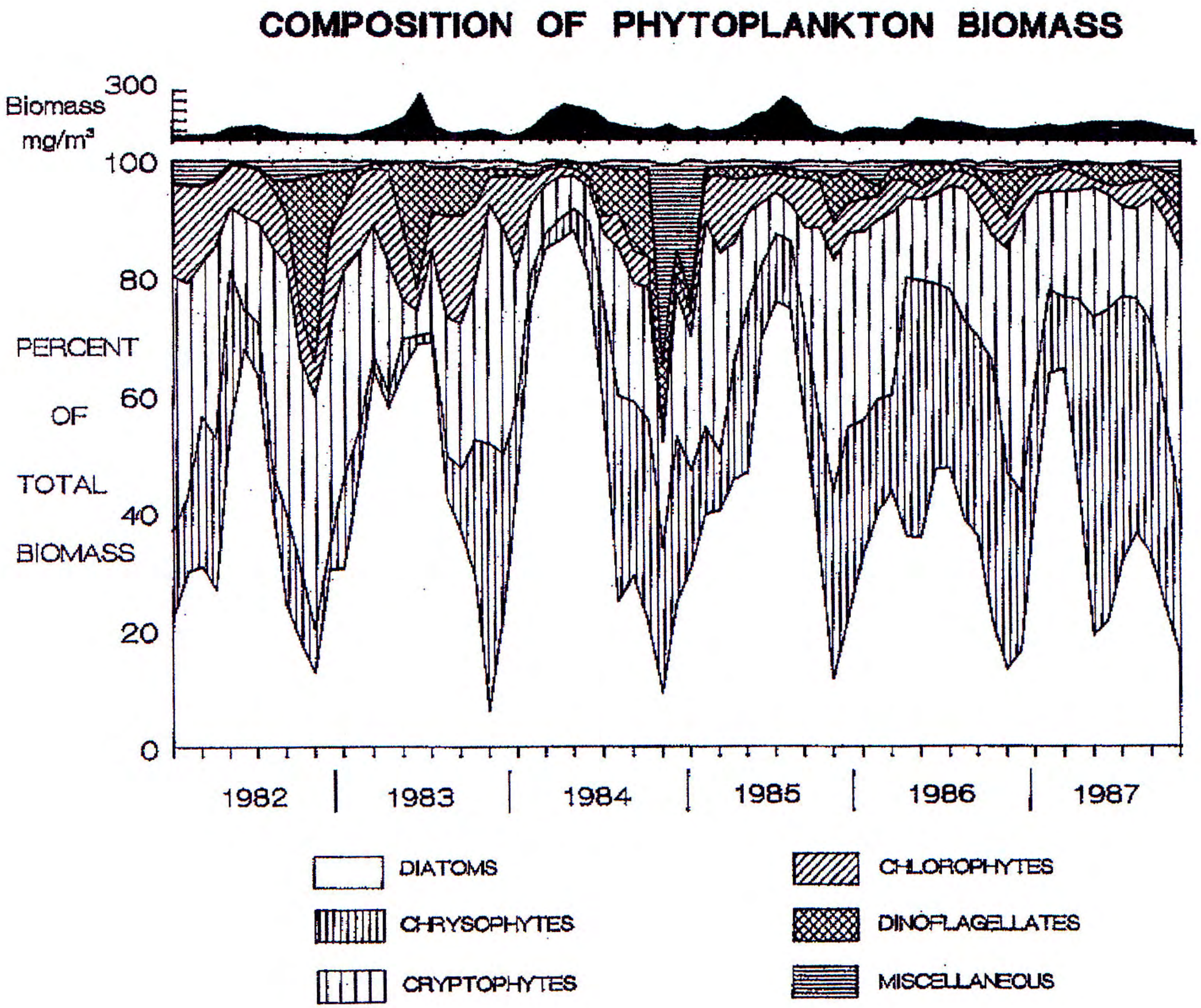


Figure 4-37—Change in the composition of phytoplankton biomass between 1982 and 1987 (from Hunter et al. 1990).

from one season to the next, but the community as a whole has typical seasonal trends. The annual sequence of phytoplankton progression begins the year with a relatively well-mixed euphotic zone. Dominance is shared between diatoms and cryptomonads. As the light duration and intensity increase and nutrient rich waters are mixed into the euphotic zone, the diatoms *Stephanodiscus alpinus*, *Asterionella formosa*, and *Aulacoseira italica* dominate the spring bloom. Generally by May, the surface waters are becoming nutrient depleted. Often chrysophytes dominate above the thermocline. Summer assemblages are marked by the spatial separation of phytoplankton communities with depth. *Cyclotella* spp. dominate in surface waters. *Synedra* spp. and *Cyclotella* spp. and chrysophytes share dominance at deeper depths. Below the thermocline (>60 m depth) cryptophytes, *Cryptomonas* spp. and *Rhodomonas lacustris*, and the green algae *Monoraphidium contortum* dominate. In late September, when the lake is still stratified and the thermocline is still well established, dinoflagellates, such as *Gymnodinium fuscum* and *Peridinium inconspicuum*, along with chrysophytes, dominate the upper water column. Below the thermocline, cryptomonads still thrive. As the thermocline decays in the autumn, more nutrients become available via mixing from deeper waters. Light intensity decreases and the upper water column has the lowest phytoplankton biomass. However, this time of year exhibits the greatest species diversity.

Lake Tahoe phytoplankton communities also exhibit spatial patterns. It has been shown that the lake has relatively homogeneous distributions of phytoplankton in a horizontal direction (Richerson et al. 1975; Eloranta and Loeb 1984). However, because of the lake's clarity and deep light penetration, phytoplankton communities separate vertically. As mentioned above, this is most apparent in summer when the water column is stratified, providing distinct growth niches. Some of the most predictable communities are in the deep chlorophyll maximum, observed during summer thermal stratification, between 40 and 80 m depth. Indeed, the euphotic zone extends beyond 125 m, and viable phytoplankton communities can survive in the aphotic zone (Tilzer et al. 1977; Vincent 1978).

The temporal and spatial predictability of the phytoplankton communities is potentially useful. Although species dominance changes annually and community composition is dynamic seasonally, general patterns remain. As eutrophication progresses, phytoplankton communities will exhibit pattern changes, such as new species introductions or deletions. Also, phytoplankton community dominance will change. Already, over the last three decades changes in the standing stock, species composition and richness, and patterns of dominance have been observed (Byron and Eloranta 1984; Hunter et al. 1990). These changes collectively indicate an alteration from historical phytoplankton data.

Nutrient concentrations of nitrogen and phosphorus in Lake Tahoe have been changing (Goldman et al. 1993). Both of these macronutrients are present in very low concentrations in the lake. Any change in the absolute concentration or in the relationship of one nutrient to another is likely to affect the phytoplankton community. Phosphorus concentrations have been linked to phytoplankton occurrence and periodicity (Lund 1965). Indeed, as Tahoe's phosphorus concentrations have decreased relative to nitrogen and become limiting, the phytoplankton communities have responded. Generally algal species that compete well for phosphorus uptake have become the dominants.

Nevertheless, phosphorus is not always the sole controlling factor. Because nitrogen is also present in such low quantities, it can at times be the limiting nutrient for phytoplankton growth. Researchers have used the ratio of nitrogen to phosphorus to predict phytoplankton community change (Tilman et al. 1982). Use of this ratio to describe Lake Tahoe's changing water chemistry is useful because the ratio takes into consideration concentrations of both nutrients. Nutrient limitation affects algae on a species-specific basis. Algal species have been shown to have different optimal N:P ratios for growth (Rhee and Gotham 1980). Organisms with lower optimal N:P ratios would be dominant in natural environments with lower ratios of available N to P and vice versa. This implies that knowing the N:P ratio in Lake Tahoe and how it has changed seasonally and interannually would go a long way toward understanding the phytoplankton community changes.

Algal communities adapt to nutrient stress. One of the adaptive strategies, increased efficiency in biochemical uptake of nutrients, has been mentioned. Other strategies include nutrient storage, heterotrophy, phagotrophy, symbiosis, and morphological changes (Vincent and Goldman 1980; Turpin 1988). These adaptations have allowed the phytoplankton to optimize chances for survival in a stressful environment. Nevertheless, species that utilize these adaptations do not follow the predictable patterns based on the N:P ratio.

Historical Evidence for Phytoplankton Community Changes—Some supporting evidence for phytoplankton species response to nutrient change comes from paleolimnological studies. Historical phytoplankton communities have been partially reconstructed from sediment cores. The remains of algal cells with silica structures, such as diatoms and scaled chrysophytes, are found within the sediment. These cells are still identifiable, often to the species level. *Cyclotella ocellata, Aulacoseira italica,* and *Stephanodiscus alpinus* were the historical diatom dominants until approximately 1960. Since 1960 the diatom dominance has changed, with increases in *Fragilaria crotonensis*, *Cyclotella glomerata, Cyclotella stelligera, Fragilaria intermedia*, and *Synedra acus*. Decreases were seen in *Aulacoseira distans* (Byron and Eloranta 1984).

Not surprisingly, 1960 corresponds to the beginning of an era of increased anthropogenic influences affecting the water quality of Lake Tahoe (Goldman 1981). Basin-wide population increases started to have dramatic effects on water quality. Many new homes and roads were built around the shoreline, and the aesthetic appeal of vacations in a mountain location made the Lake Tahoe basin an increasingly popular destination. The Lake Tahoe basin experienced increased recreational use, soil disturbances, and nutrient loading from leaching septic tanks. Both nitrogen and phosphorus additions had an impact on the algal community composition and growth rates.

While nitrogen inputs may have had the most dramatic impact on algal growth rates (e.g., the shift in N-P limitation discussed above), it was the phosphorus loading that was probably responsible for the phytoplankton species shifts. Increased phosphorus input clearly occurs with soil erosion, as phosphorus compounds often attach or become adsorbed to soil particles. Additionally, phosphorus inputs from leaching septic tanks may have been very significant (Collingwood 1978). The sewage effluent was rich in phosphorus from human excrement, but also, notably, very high soluble phosphates came from synthetic detergents used in household laundry. Indeed, this source of phosphorus input to aquatic environments led to bans on the use of phosphates in detergents.

By the early 1970s sewage effluent at Lake Tahoe was no longer a significant issue. A basin-wide sewage system was installed and operational. Untreated effluent was piped out of the basin or sent to tertiary treatment facilities; however, a number of large-scale sewage spills have occurred since this time. In addition, building and road construction within the Tahoe basin was limited by regional governing agencies. Builders were required to employ tactics to reduce soil erosion; as a result, phosphorus loading was reduced.

These years of cultural eutrophication brought many changes to the phytoplankton community. Bioassay enrichment experiments began to show shifting nutrient limitation, with increased response to phosphorus additions (Goldman 1988). Further evidence of a changing chemical regime came from the appearance and then later disappearance of *Fragilaria crotonensis*. Byron and Eloranta (1984) reported that the diatom *F. crotonensis* had very low abundance prior to 1960. However, this species in particular, had enormous increases in abundance after 1960. It clearly dominated the phytoplankton assemblage (Goldman 1974). However, by 1975 its abundance decreased, and by 1980 it virtually disappeared from the lake (Hunter et. al. 1990).

The decrease in phosphorus loading to Tahoe had an immediate impact on populations of *F. crotonensis*. Tilman et al. (1982) reported that *F.*

crotonensis does not compete well in phosphorus-limited environments. Indeed, simultaneous to the *F. crotonensis* decline the phytoplankton community had an increase in the pennate diatoms *Asterionella formosa* and *Synedra* spp. Both of these species have been reported to exhibit more efficient uptake of phosphorus and therefore are better competitors than *F. crotonensis* in phosphorus-poor waters (Tilman et al. 1982).

Cyclotella spp. also has an affinity for phosphate-depleted environments; therefore, it is not surprising that this genus has increased in abundance, especially because phosphorus has become more limiting. Byron and Eloranta (1984) reported decreases in *C. ocellata* and increases in *C. stelligera* and *C. glomerata* since 1960. The decrease in *C. ocellata,* it might be argued, could be due to direct competition among species of the same genera. These species are similar in size and nutrient requirements. The fact that the genus has increased its representation in the phytoplankton community is a rather strong testament to the success of the group.

The chrysophytes also have been reported to be good competitors for phosphorus (Lehman 1976; Reynolds 1980; Sommer and Kilham 1985; Sandgren 1988). Lake Tahoe phytoplankton showed increased abundance of *Dinobryon*, *Chrysochromulina*, *Uroglena*, *Kephrion*, and *Synura* since the early 1980s. Indeed, beginning in the mid-1980s *Uroglena americana* began appearing in blooms that never had been reported before.

Phytoplankton Modes of Nutrient Absorption and Competition—Other phytoplankton assemblage changes tend to favor species with adaptive strategies for success in phosphorus-depleted systems. There have been increases in phytoplankton species that have the ability to internally store limiting nutrients. *Asterionella formosa*, in addition to having an affinity for low phosphorus concentrations, is capable of luxury consumption of phosphorus (Nalewajko and Lean 1980). This species can absorb phosphorus in the dark and in excess of its immediate requirements. Mackereth (1953) reported that *A. formosa* could store 25 times the minimum cell content of phosphorus before spring growth. This strategy for survival is considered secondary to those species that have low half saturation rates for phosphorus uptake (Sommer 1984).

There also have been increases in phytoplankton species that supplement nutrient requirements by phagotrophy, or ingestion of particles. This survival strategy appears to be an important pathway for energy flow in lakes. Phagotrophy has been reported for many of the chrysophytes, such as *Dinobryon*, *Chrysophaerella*, *Uroglena*, *Ochromonas*, *Chromulina*, and *Chrysococcus* (Bird and Kalff 1987). All of these genera have been found in Tahoe waters where the ability to ingest nutritious particles would provide a competitive advantage.

Since 1980 there has been a marked increase in flagellated phytoplankton in Lake Tahoe waters (Hunter et al. 1990). Algae motility has been recognized as an adaptive advantage (Salonen et al. 1984) as motile cells thereby have the ability to move from one space to another for nutrient retrieval or to improve their exposure to light. Algae migrate to deeper depths at night for nutrient retrieval and then move back toward the surface in daylight to proceed with photosynthesis. Some of these flagellated groups of algae have been discussed previously, but the flagellated algal group, the cryptophytes, also has increased in abundance. *Cryptomonas* spp. is especially noted for using motility to improve nutrient acquisition (Rott 1988). Both *Cryptomonas* spp. and *Rhodomonas* spp. dominate the Tahoe phytoplankton assemblage during some parts of the year (Hunter, unpublished).

Another competitive advantage of flagellates is their generally small size. Low nutrient conditions favor cells that have high surface to volume ratios (Grover 1989). Other variables being equal, smaller cells would have faster uptake and turnover of nutrients. The Lake Tahoe phytoplankton community has exhibited a general morphological shift in phytoplankton species. There have been increases in cells with long slender shapes (e.g., pennate diatoms) and overall increases in small cells with an ovoid shape. Interestingly, the biomass calculations of the phytoplankton cannot fully account for the rapid increases in algal growth rates. This increase could, in part, be due to the relatively more rapid metabolism of small cells. The smaller cells, while more abundant and efficient at nutrient uptake and turnover, do not contribute much to the total biomass of the phytoplankton.

Predictions—Changes in the Lake Tahoe phytoplankton community have accurately reflected changes in the aquatic chemical environment. If nutrient loading continues, where both nitrogen and phosphorus concentrations increase, one or more of the following scenarios might occur:

- **Primary productivity and phytoplankton standing stock will increase**. As nutrient concentrations increase, the primary production and algal standing stock will increase (Schelske et al. 1974). The typical seasonally bimodal production peaks should increase in intensity and length. The periods of low production may become shorter and less pronounced.
- **Species richness of phytoplankton will increase**. When productivity increases, so should species richness. Even small changes in primary productivity should create large changes in species richness (Eloranta 1999).
- **Phytoplankton community dominants will shift**. As the physical and chemical environment changes, the phytoplankton community will respond with increased abundance in species that compete well. Moore (1979) reported that increased nutrient loading favors flagellates at the expense of diatoms. Cells also will tend to be smaller, with an overall increase in surface area to volume ratio.
- **The deep chlorophyll maximum, perhaps the most stable phytoplankton niche, will exhibit changes in species assemblage and distribution**. In thermally stratified waters, the biomass maximum is just below the thermocline (>40 m depth). At this depth there is enough light and nutrients to support algal growth. However, with increasing algal biomass, the clarity of Lake Tahoe will decrease. Light will not penetrate as deeply, and light conditions favorable for the algae will occur at shallower depths. The phytoplankton might have sufficient light to
- grow only within or above the thermocline, where nutrients are very limited. This change in nutrient conditions may strongly affect the species assemblage.

Most of these changes will happen simultaneously. However, the phytoplankton community dynamics will be the most responsive indicator of change. Efforts to understand these changes can provide strong management criteria for Lake Tahoe's primary production.

One could argue that phytoplankton identification and enumeration do not offer any advantages over the much quicker chlorophyll *a* measurement as a water quality indicator and management tool. The chlorophyll *a* measurement would provide useful information about changes in algal biomass, but it will not detect changes in the species composition of the phytoplankton community, only a relative change in algal biomass. The chlorophyll *a* measurement is an easy rapid method that fails to measure the one component that makes the phytoplankton such a good indicator of change.

In addition, and arguably most importantly in terms of lake clarity, knowing the species assemblage and relative abundance will provide more useful information to models predicting light attenuation contributed by the phytoplankton. Water clarity is strongly affected by the amount of light scattering in the water column, which in turn is closely related to the number and characteristics of particles in the water. However, the chlorophyll assay will not measure light scattering, cell characteristics, or population. It will measure light absorption by the phytoplankton but this parameter may not correlate as well with other measurements of lake clarity (Jassby 1999).

Growth of Attached Algae

Among the first visible evidence of eutrophication of Lake Tahoe was the increased amount of attached algae, or periphyton growth, along the shoreline in the 1960s. Goldman (1967b) indicated that when he first began studying the lake in 1958, the rocks along shore showed only slight growth of attached algae. However, in the spring of 1967, significant periphyton was found in the shallows on boat hulls, and waves piled up mats of the detached material along the shore. Increased growth of periphyton was apparent to a largely shore-bound populace and provided additional, and very visual evidence that changes were occurring. This increase in periphyton growth coincided with the period of rapid growth and development within the basin during the 1960s and could be attributed to an increased nutrient loading from the surrounding watershed via stream and ground waters (Goldman 1974, 1981; Loeb and Goldman 1979). Widespread periphyton growth in the near-shore during the spring remains a characteristic of the shoreline today. Many studies have been done that have looked at the biology and distribution of periphyton in Lake Tahoe (Goldman and de Amezaga 1975; Loeb 1980; Loeb and Reuter 1981; Goldman et al. 1982; Reuter 1983; Reuter et al. 1983; Loeb and Reuter 1984; Loeb and Palmer 1985; Loeb 1986; Loeb et al. 1986; Aloi 1986; Reuter et al. 1986a, b; Aloi et al. 1988). The following presents some of the findings of these studies with emphasis on factors controlling growth, distribution, and evidence available on long-term trends for periphyton growth in the lake.

Periphyton Community Species Composition

Periphyton grows in the littoral (shore) zone of Lake Tahoe, which may be divided into the eulittoral zone and the sublittoral zone, each with distinct periphyton communities. The eulittoral zone is the shallow area between the low and high lake level (0 to 2 m) and is significantly affected by wave activity. This zone represents only a very small percentage (<1 percent) of the total littoral area. Substrata within this region desiccate as the lake level declines, and periphyton must recolonize this area when lake level rises. The sublittoral zone extends from the bottom of the eulittoral to the maximum depth of photoautotrophic growth. The sublittoral zone remains constantly submerged and represents the largest littoral benthic region of Lake Tahoe.

The eulittoral zone community typically is made up of filamentous green algae and filamentous diatom species. On rock surfaces just beneath the air-water interface (i.e., the uppermost region of the eulittoral), a green filamentous alga, *Ulothrix zonata* is often found. Extending from just below this growth to a depth of approximately 2 m, a brownish or whitish growth of algae covers the bottom of the eulittoral zone. This growth is strongly dominated by one species, the stalked diatom, *Gomphoneis herculeana*. In fact, the growth of this species is so great at times that it resembles a thick shag carpet on the bottom. *Synedra ulna* and various other diatoms are found growing in association with *Gomphoneis*. *Cyanophycean* (blue-green) algae are generally absent from the eulittoral zone.

The upper portion of the sublittoral zone (2 to 80 m) is dominated by blue-green algae capable of nitrogen fixation, including *Tolypothrix*, *Calothrix*, *Nostoc*, and *Scytonema*, which are heterocystous filamentous genera, and *Gloeocapsa*, which is a unicellular, sheathed blue-green algae. These algae firmly attach to the rock surfaces. Filamentous green algae and diatoms also are found in the sublittoral, but they make up a small part of the total biomass. Beneath about 80 meters, blue-green algae species drop out and diatoms and green algae become dominant; below 100 meters, an encrusted green algae may be found. The maximum depth at which periphyton has been found growing on rocks in Lake Tahoe is 198 meters.

Seasonal Patterns of Periphyton Growth—The periphyton in the eulittoral zone is more seasonally dynamic than that of the sublittoral community. Typically, growth of the eulittoral periphyton begins to increase in the late winter, reaches maximum growth in the spring, then decreases in the summer (Figure 4-38). In some years, the eulittoral periphyton also may show a secondary increase in growth during the fall. The range between minimum and maximum annual growth is typically greater for the eulittoral than for the sublittoral community. Following peak growth, the algae may slough off the rocks, and the growth of algae often remains low throughout the fall and winter. Aloi et al. (1988) found that at eulittoral sites with high accumulation of biomass (Pineland and Rubicon Point), sloughing of the entire algal mat occurred after the spring

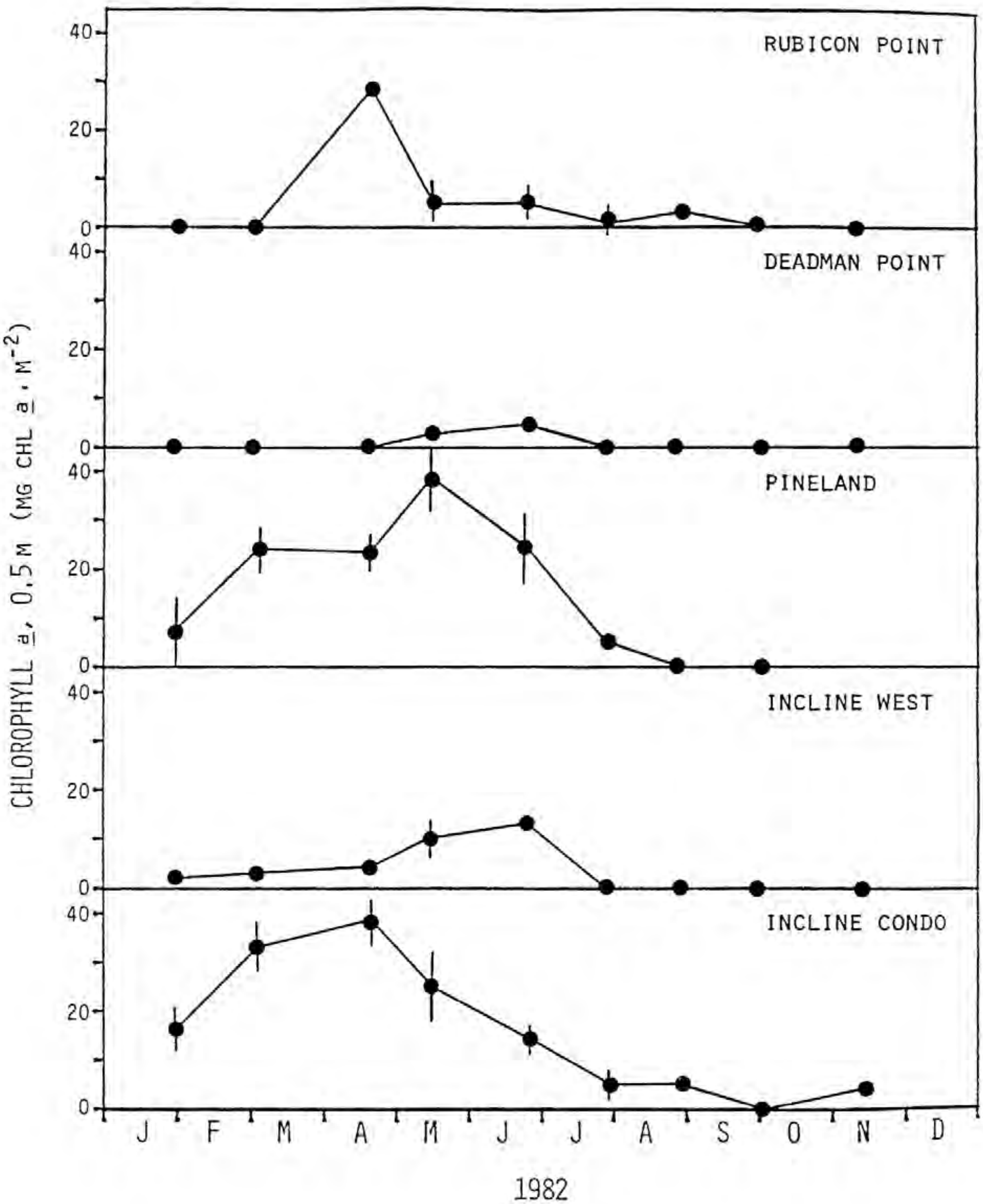


Figure 4-38—Spatial and temporal distribution of periphyton algae at a depth of 0.5 m in Lake Tahoe (from Loeb and Reuter 1984).

maximum. At sites with lesser accumulations of biomass (e.g., Deadman Point and Sand Point), the decrease in algal biomass was a slower process and appeared to be due to a combination of gradual attrition of periphyton biomass, combined with minimal regrowth.

The sublittoral periphyton community generally has less dynamic seasonal biomass fluctuations than the eulittoral community (Loeb et al. 1986). The baseline amount of growth remains more consistent for the sublittoral community. In contrast to the periphyton of the eulittoral zone, this community persists on the rock surfaces and remains viable throughout the year (Reuter et al. 1986a). The seasonal variations of the sublittoral community are generally less predictable than for the eulittoral community (Loeb and Palmer 1985). It was difficult to distinguish a consistent pattern of seasonal biomass for this community from 1982 to 1985 monitoring for three sites studied (Pineland, Deadman Point, and Rubicon Point) (Loeb et al. 1986). In addition, seasonal maxima for chlorophyll biomass at 2 m did not necessarily coincide with seasonal maxima slightly deeper at 8 m at each site.

Spatial Variation in Growth—Several studies have looked at the spatial distribution of periphyton. These studies have included spatial variability of periphyton on natural substrata (Loeb 1980; Loeb and Reuter 1984; Loeb and Palmer 1985; Loeb 1986; Loeb et al. 1986; Aloi 1986; Aloi et al. 1988) and spatial variability of periphyton colonization of artificial substrata (i.e., substrata, such as glass slides placed at sites to specifically measure periphyton growth) in the littoral zone (Goldman and de Amezaga 1975; Loeb et al. 1986; Aloi 1986; Loeb 1987). A consistent finding of these studies has been an association between development and disturbance in the watershed and increased periphyton growth nearshore.

To demonstrate the association between periphyton biomass and land disturbance on adjacent land, Loeb (1986) compared eulittoral chlorophyll *a* biomass data for four stations. Two stations (Pineland and Incline Condo) were adjacent to developed areas, and two stations (Incline West and Deadman Point) were adjacent to undeveloped areas. Greater amounts of periphyton were found at the developed stations than at the two undeveloped stations. The ratios among the maximum amount of biomass at each location (Deadman Point : Incline West : Incline Condo : Pineland) during each of the three years studied showed a persistent spatial relationship: 1982 (1:3:8:8), 1983 (1:1:6:10), and 1984 (1:2:4:13). Available light energy and water temperature did not vary significantly enough to explain the spatial differences in periphyton biomass among sites, especially between Incline Condo and Incline West, which were only 200 meters apart. The most likely cause for the differences among stations was nutrient availability. The Incline Condo station, which had higher periphyton biomass, was adjacent to a condominium development, which Loeb estimated used about 0.13 to 0.16 MT of nitrogen and 0.10 to 0.13 MT of phosphorus in fertilizer per year on a lawn upslope of the station. The Incline West site, which had less biomass, is only 200 meters away, adjacent to an undeveloped area. The Pineland site, which had higher biomass, is adjacent to the developed area of Pineland in the Ward Creek watershed on the west shore. Deadman Point is adjacent to an undisturbed area on the east shore, with the nearest development one kilometer away.

While there is strong evidence of an association between increased periphyton biomass and development or disturbance in the adjacent areas of the watershed, some variations from this pattern do occur. For instance, Rubicon Point is far from significant land-based disturbance, but consistently high biomass was measured at this station from 1983 to 1985 (Aloi et al. 1988). Aloi et al. hypothesize that upwelling of nutrient-rich profundal waters occur here, stimulating algal growth. High chlorophyll *a* biomass of periphyton also was measured near Sugar Pine Point, a relatively undeveloped area. Periphyton grow on isolated boulders at this site, separated by areas of sandy bottom. Aloi et al. (1988) speculated the wide separation between boulders may contribute to decreased competition for nutrients and increased growth of the periphyton.

Periphyton Primary Production—Periphyton primary productivity has been monitored in both the natural eulittoral and sublittoral periphyton communities (Loeb 1980; Loeb and Reuter 1984;

Loeb and Palmer 1985; Loeb et al. 1986; Aloi 1986). Aloi (1986) measured primary productivity in the eulittoral zone at Rubicon Point from January to October 1984 and from February to May 1985. She found primary productivity to be low during the late winter, to increase during the spring, and to decline again through the summer. Productivity ranged from 3 to 10 mg C/m^2/hr during low growth during late winter-early spring and late-summer 1984 and reached a maximum of 203 mg C/m^2/hr in early July 1984.

Primary productivity of the sublittoral zone showed less variability over the same period; at 2 m, productivity ranged from 1.44 to 9.72 mg C/m^2/hr, at 8 m, productivity ranged from 0.97 to 13.97 mg C/m^2/hr, and at 16 m, productivity ranged from 0.60 to 4.22 mg C/m^2/hr. Sublittoral primary productivity measurements were made over a longer period from February 1982 to May 1985 (Loeb et al. 1986) and in general indicated a slightly greater fluctuation, with slightly higher maximum productivity values at 2 m and 16 m in 1982 (14.53 and 10.43 mg C/m^2/hr, respectively).

The contribution of periphyton primary production to overall lake primary production is thought to be small, relative to that from the phytoplankton. The littoral zone productivity (phytoplankton plus periphyton production) of Lake Tahoe has been estimated to be about 10 percent of the lake's total annual primary production (Goldman and de Amezaga 1975; Goldman 1981).

Periphyton primary productivity measurements provide a measure of the growth rate of the periphyton (i.e. the production of new organic matter). This new production can be considered detrimental when it produces unaesthetic slimy coatings on rocks nearshore, which also make wading and swimming less enjoyable, when it coats boat hulls, and when decaying mats of periphyton slough from rocks and accumulate along the shoreline. New production by the periphyton also may be utilized by secondary producers, including crayfish, fish, and insects and may be incorporated into the food chain in Lake Tahoe. The crayfish *Pacifastacus leniusculus* has been found to derive 65 percent of its diet from periphyton (Flint 1975).

Factors Affecting Growth of Periphyton—Several physical, chemical, and biological factors may affect the growth of periphyton in Lake Tahoe. The period of maximum periphyton accrual in the eulittoral zone in the spring coincides with increasing flux of solar radiation, lake temperature, and availability of nutrients. Light availability is a fundamental factor affecting photosynthesis and the primary productivity (growth rate) of periphyton. Solar radiation follows a typical cycle of minimum solar radiation in early winter, a rapid increase in the spring to an early summer maximum, and a rapid decrease in the fall back to the minimum. The rapidly increasing solar radiation in the spring may contribute to increased growth of periphyton in the spring. Water temperature is another important factor that could affect productivity of the algae. The slight increases in water temperature that occur in the spring cannot alone account for increases in biomass seen. The increased growth of eulittoral algae in the spring is thought to be largely the result of increased availability of nutrients (Loeb and Reuter 1984). Algal bioassays have shown that addition of nitrogen alone and occasionally phosphorus alone can stimulate periphyton growth and that the combination of nitrogen and phosphorus often causes the greatest growth when significant responses are observed (Loeb 1986; Loeb et al. 1986; Loeb 1987). However, periphyton bioassays have not been run since the mid-1980s, near the time when the dependence of lake phytoplankton on phosphorus was found to increase dramatically. The snowmelt generally occurs from April to June, when much of the annual tributary loading of nutrients occurs. In addition to nutrient inputs from streams, ground water inputs with associated nutrients are thought to be at a maximum during this time (Loeb and Goldman 1979). Lake mixing also contributes nutrients in late winter, which could affect the growth of periphyton in the spring. Reuter et al. (1986b) provided evidence that the eulittoral periphyton, while not having a high physiological affinity for nitrogen, were able to effectively utilize nutrients because the breaking waves in their shallow environment enhanced the rate of nutrient diffusion into the cells.

Some factors that affect the accrual of the sublittoral periphyton biomass may be generally similar to those that affect the eulittoral periphyton community (Loeb et al. 1986). However, it is also possible that differences in resource availability, physiology, and physical factors in the sublittoral may lead to different growth responses. For instance, the sublittoral periphyton can utilize atmospheric N_2 as a source of nitrogen, which allows these algae to maintain growth when inorganic nitrogen is scarce and which could result in different growth responses than for the eulittoral periphyton under certain conditions of inorganic nitrogen availability. Additional information on factors controlling growth in this community is needed.

Periphyton Nitrogen Fixation—The upper portion of the sublittoral zone (2 to 60 m) is dominated by heterocystous blue-green algae, or algae that are capable of nitrogen fixation. These algae can utilize atmospheric nitrogen for growth, which appears to be a successful adaptive strategy for survival in N-deficient environments, such as Lake Tahoe (Reuter et al. 1986a). This is in contrast to the eulittoral periphyton and lake phytoplankton, which require inorganic nitrogen (NO_3^-, NH_4^+) for growth. Reuter (1983) found that the sublittoral community is perennial and actively fixes N throughout the entire year. Seasonal rates of N-fixation ranged from 4 to 561 μg $N/m^2/h^1$, with a distinct summer maximum and winter minimum. The seasonal cycle of N-fixation in Lake Tahoe appears to be related primarily to temperature. Factors that have been found to also influence N-fixation in other systems include levels of organic nitrogen, phosphorus and iron (Horne 1978), and their possible effects in Lake Tahoe cannot be dismissed.

During nitrogen fixation, atmospheric nitrogen (N_2) is incorporated into algal biomass, which may later be mineralized to inorganic forms and become available to support phytoplankton production; therefore, it is a source of nitrogen input for the lake. Reuter et al. (1986a) estimated the loading rate of nitrogen resulting from nitrogen fixation was 0.03 kg N/ha (of lake surface)/yr. When this rate is compared to other sources of inorganic nitrogen loading into Lake Tahoe, N loading from periphyton nitrogen fixation is very small, <1 percent of total annual dissolved inorganic nitrogen loading.

Evidence Available for Long-term Trends in Periphyton Growth—Early observations indicate that a significant change from relatively small amounts of periphyton growth in the past to increased amounts of growth took place during the 1960s. As discussed above, Goldman (1967b) indicated that when he first began studying the lake in the late 1950s, the rocks along the shore showed only slight growth of attached algae. However, in the spring of 1967, he observed much periphyton growth in the shallows, on boat hulls, and mats of the detached material piling up along shore. Goldman and de Amezaga (1975) studied periphyton growth around the lake in 1971 and found that in the spring and early summer inshore areas were visibly green due to periphyton growth, with particularly heavy growth found in the vicinity of some stream mouths.

Goldman and de Amezaga (1975) compared the growth of periphyton on artificial substrata (Pyrex cylinders) at many sites around the lake in 1971 and discerned a trend of increased periphyton growth associated with human activity in the watershed. They found that the highest growth rates were recorded near stream mouths where human activity is the greatest, such as Ward Creek and Incline Creek, and that in general, lower growth was found in areas of least tributary influence, such as along the sparsely populated east shore. As indicated above, many subsequent studies have confirmed a trend of increased periphyton growth adjacent to areas of developed or disturbed portions of the watershed. This increased periphyton growth is thought to be largely due to the increased nutrient loading associated with the land development or disturbance in the watershed and represents a change from the expected natural growth pattern.

Quantitative data for periphyton biomass and primary productivity are available for certain years from 1971 to 1992, which should provide additional information on trends; however, a thorough statistical analysis of these data has not yet been made. Only very general observations were attempted here, based on the available biomass data. Only recently has funding been reinstated to carry on periphyton monitoring.

Comparative data are available for periphyton biomass on natural rock substrata in the lake for 1978 (Loeb 1980), 1982 to 1985 (Loeb and Reuter 1984; Loeb and Palmer 1985; Loeb et al. 1986), 1986 to 1987 (Loeb 1987), and 1989 to 1992 (TRG, unpublished). Chlorophyll biomass data for the Rubicon Point 2-meter and 8-meter sites are available for several of the above periods. Sublittoral chlorophyll *a* biomass in 1978 (February to November) at 2 meters ranged from about 5 to 15 mg/m^2, from 1982 to 1985 it ranged from 7 to 52 mg/m^2, and from 1989 to 1991 it ranged from 12 to 37 mg/m^2. At 8 meters, chlorophyll biomass ranged from about 14 to 35 mg/m^2 in 1978, from 12 to 73 $mg\ m^{-2}$ from 1982 to 1985, and from 10 to 37 mg m^{-2} from March to June of 1992. These data indicate variability in the sublittoral chlorophyll *a* has occurred, but no long-term trend of either increase or decrease in biomass is apparent from these ranges.

Chlorophyll *a* biomass data is available for Pineland eulittoral (0.5 m) periphyton growth from 1982 to 1985 (Loeb et al. 1986), from 1986 to 1987 (Loeb 1987), and from 1989 to 1992 (TRG, unpublished). This data indicates that substantial year-to-year variability in seasonal maximum biomass has occurred. However, it is difficult to discern any long-term trend in overall annual growth from 1982 to 1992. This observation is not inconsistent with the more general finding that periphyton biomass in Lake Tahoe has increased over time. In the studies cited above, periphyton at a single location was assessed over time. The data imply that more of the shoreline may be now experiencing periphyton growth.

A noteworthy trend from these observations is the consistent presence of the blue-green algae in the sublittoral zone from at least 1971 to 1992, when sampling was terminated. It is possible that this community has existed at some level of growth in Lake Tahoe for a long time. Studies of other oligotrophic lakes, including pristine Crater Lake in Oregon, have shown similar sublittoral blue-green algal communities (Loeb and Reuter 1981). The presence of filamentous green algae and diatoms in the eulittoral zone of Lake Tahoe is similarly a characteristic of other oligotrophic lakes. Changes in the *amount* of growth of the eulittoral community in Lake Tahoe have been a visible indicator of eutrophication in the lake.

What is known regarding phosphorus and nitrogen in Lake Tahoe and regarding the long-term behavior of these nutrients?

Jassby et al. (1995) examined the long-term change in Lake Tahoe's water chemistry for nitrate (NO_3^-) and THP. These nutrients were selected because of their importance to algal growth and eutrophication and because of the availability of an extensive database from which a statistical evaluation of long-term trends could be made. A significant portion of the discussion below comes directly from that analysis.

Due to the vagaries of funding sources and the varying interests of the many TRG researchers over the past three decades, the water chemistry data set for Lake Tahoe varies depending on the specific nutrient species in question. The longest records are for nitrate ($NO_3^- + NO_2^-$) and THP at the mid-lake station, which have been measured since 1973. Ammonium (NH_4^+) measurements are available since 1983, TKN since 1990, and SRP, TDP, and PP since 1992 at the mid-lake station. Although these latter series are inadequate for studying long-term variability, they enable an estimate of lake nutrient reservoirs. The TRG mid-lake station overlies the deepest point in the lake (505 m) and allows estimates of whole-lake nutrient content. Samples are collected monthly at depths of 0, 10, 50, 100, 150, 200, 250, 300, 350, 400 and 450 meters.

Nutrient Reservoirs

Data from 1992 and 1993 allows an examination of the size of the reservoir or pools for various forms of nitrogen and phosphorus in Lake Tahoe. By definition, total-N (TN) and TP contain both dissolved (<0.45 μm) and particulate (>0.45 μm) components. Typically, water clarity is most affected by the particulate fraction; however, there may be significant transformation between particulate and dissolved material through biological uptake, mineralization, dissolution, and other processes. These processes occur on a multitude of time scales extending from seconds to years. Many of the individual forms of nitrogen and phosphorus show significant seasonal and interannual variability depending on the degree of input from the airshed and watershed and lake biogeochemistry. This section is focussed primarily on the annual, interannual, and decadal patterns of Lake Tahoe's nitrogen and phosphorus content.

Nitrogen

The mean whole-lake concentration of TN for Lake Tahoe in 1992/1993 was 65 μg/L. Monitoring and research data summarized by Marjanovic (1989) indicates that particulate-N (PN) comprises nearly 15 percent of TN, or in this case 9 μg/L. The majority (85 percent) of TN occurs in the dissolved form either, as dissolved organic-N (DON) or dissolved inorganic-N (DIN). DIN consists of nitrate (15 μg/L) and ammonium (1-2 μg/L) and accounts for approximately 25 percent of TN. At a mean concentration of approximately 40 μg/L, DON constitutes the largest N-fraction at 60 percent. Nitrate and ammonium are known to be readily and directly available for algal growth; however, the bioavailability of DON, not only in Lake Tahoe but in the world's lakes and oceans in general, is not well understood.

DON includes a wide array of chemical compounds, ranging from some of the more labile, or easily broken down, compounds, such as certain amino acids, to more refractory N-containing compounds, which resist bacteria breakdown. Lake Tahoe is similar to most other lakes that also contain large portions of their TN pool as DON. The ratio of organic-N (as PN+DON) to DIN during the 1992/1993 period was on the order of 4:1. From 1984 to 1989, this ratio in Lake Tahoe was 5:1 (Marjanovic 1989). Because the PN+DON pool is large, relative to DIN, even a relatively small conversion could have a major effect on DIN. For example, a mineralization rate that is only 10 percent higher than the current rate (unknown at this time) would result in a 50 percent increase in biologically available DIN. Moreover, mineralization of only one to two percent of the DON pool in Lake Tahoe in roughly equal to the annual DIN load from atmospheric deposition and stream runoff combined. This underscores the importance of considering nutrient cycling and bioavailability in any discussion of lake nutrient dynamics. Difficulties in methodologies make quantification of the mineralization of PN+DON to DIN unreliable; highly sophisticated research is needed to address these questions. Presently only a limited number of oceanographers are working on this issue.

Based on the preceding data, the approximate whole-lake content for various N-fractions are as follows:

Fraction	Metric Tons*
NH_4^+	219
$NO_3^- + NO_2^-$	2,344
PN	1,409
DON	6,216
TN	10,188

In comparison to the estimated TN load of approximately 350 MT per year (see nutrient budget), this corresponds to a specific loading rate of $0.034 \cdot yr^{-1}$. Viewed in a different light, this also means that in the absence of any loss (e.g., outflow, sedimentation, denitrification) and no change in loading, it would take approximately 30 years of input to double the existing lake TN content. Clearly, the response time for nutrient concentrations in Lake Tahoe is long as a result of its large volume (156 km^3), great depth (505 m), slow hydrologic flushing rate (650 to 700 years) and relatively low loading rates relative to these hydrogeological features.

Phosphorus

Mean, whole-lake TP concentration in 1992/1993 was 6.3 μg/L. PP, at a calculated concentration of 0.6 μg/L, was approximately 10 percent of this larger pool. As observed for nitrogen, most of the lake's P is in the dissolved form; TDP was determined at 5.7 μg/L. Further dividing TDP, ortho-P ($PO4^{-3}$ or SRP) was 2.1 μg/L, and dissolved organic-P (DOP) was 3.6 μg/L. Total acid-hydrolyzable $PO4^{-3}$ (THP) represents that P-pool converted to ortho-P following a relatively mild acid

* One metric ton = 1,000 kilograms, or 2,204.6 pounds

digestion during chemical analysis. This is intended to represent the potentially bioavailable-P. THP from 1992 to 1993 was 2.6 μg/L, and, as expected TP<THP>PP.

Typically, when algal growth is active ortho-P is rapidly incorporated into phytoplankton and bacterial biomass. Hatch et al. (in press) tested the response of Lake Tahoe phytoplankton to stream water additions of various particle size classes. Over the one week course of these experiments, the dissolved fraction of stream water contributed most (75 to 90 percent) of stimulation to Lake Tahoe phytoplankton. Within the DP-pool, algal response was best related to ortho-P ($p=0.005$) and less related to DOP ($p=0.051$).

The approximate whole-lake content for various P-fractions are as follows:

Fraction†	Metric Tons
SRP	340
TDP	901
DOP	561
THP	403
PP	91
TP	992

In comparison to the estimated TP load of approximately 42.6 MT per year (see nutrient budget), this corresponds to a specific loading rate of $0.043 \cdot yr^{-1}$. In the absence of loss and with no change in loading, it would take approximately 23 years of input to double the existing lake TP content.

Spatial Variation

A comparison of the mean annual concentrations of nitrate and THP in the euphotic zone at the TRG's mid-lake and index stations provides evidence that the mid-lake location, in general, is representative of most of the lake. The index station is positioned on the lake's western shelf, approximately two kilometers off-shore. It overlies 150 m of depth and is just south of Blackwood Creek. In this analysis, the euphotic zone is taken to be 0 to 100 meters, which approximately corresponds to the depth where light transmission is one percent of surface light; most of the lake's phytoplankton growth occurs in this region.

For the period 1985 through 1993, nitrate at the index station was 4.9±0.8 μg N/L and slightly higher than the average concentration of 4.5±1.0 μg N/L at the mid-lake station (average of mean annual concentrations). The largest annual difference in nitrate between these two locations was in 1992, when NO_3^- at the index station was 3.6 μg N/L as compared to 2.8 at mid-lake. THP was virtually identical at these two stations, with the average of the mean annual concentrations equal to 2.9 μg/L for mid-lake and 3.0 μg/L for the index station. As for nitrate, the largest difference between these two stations occurred in 1992, when the index THP concentration was 20 percent greater (i.e., 2.4 μg/L vs. 2.0 μg/L).

Long-term Chemistry Records

According to Jassby et al. (1995), the monthly series of mean whole-lake NO_3^- displays considerable variability at the scale of months and years but only a weak long-term trend that is due to a rise prior to 1977 (Figure 4-39). To assist in the statistical analysis of this data, a 12-term moving average was calculated; because there were too many missing data points prior to 1980, data earlier than this date were not included. The moving average helps to filter out much of the seasonal variability and focus on interannual and long-term changes. The average data shows persistence in the form of quasi-cyclical behavior; for example, between 1980 and the mid-1990s, NO_3^- appeared to peak on a somewhat regular three- to five-year interval. Thiel slopes were calculated from the time series and were used as indicators of long-term trend. For NO_3^-, the Thiel slopes were positive for every month but were only statistically significant for August. These data indicate that over the period of record, there was an increase in NO_3^- concentration in Lake Tahoe during each of the 12 months but that this rise was significant ($p<0.05$) for August. However, the occurrence of a positive Thiel slope during every month is highly unlikely due to chance alone ($p=0.0002$).

† By definition, TP = PP +TDP and TDP = SRP + DOP

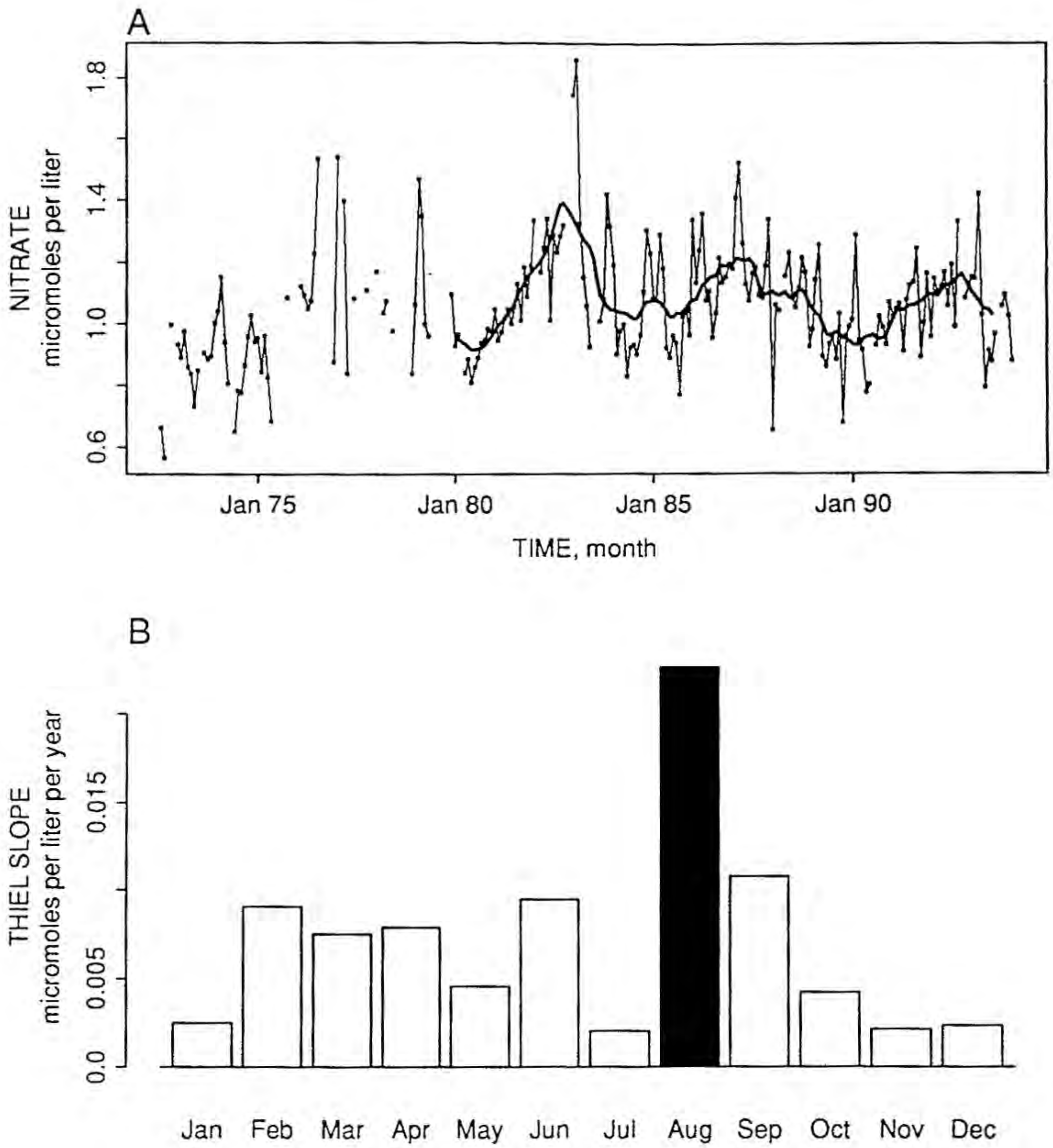


Figure 4-39—Presentation of long-term nitrate water chemistry data from Lake Tahoe. Thiel slopes show an increase in concentration during each month; however, this increase is only statistically significant in August. 1 micromole per liter = 14 µg per liter (from Jassby et al. 1995).

As in the case for NO_3^-, the monthly THP time series exhibits much seasonal variation but no unequivocal long-term trend (Figure 4-40). Between 1980 and 1993, the 12-term moving average even suggests some downward movement for whole-lake THP. Nine months exhibit a negative Thiel slope, but only two of these slopes—March and April—are significant ($p<0.05$).

Given the statistically significant change in algal primary productivity and water clarity since continuous measurements began in 1968, it is important to ask why the time series for NO_3^- and

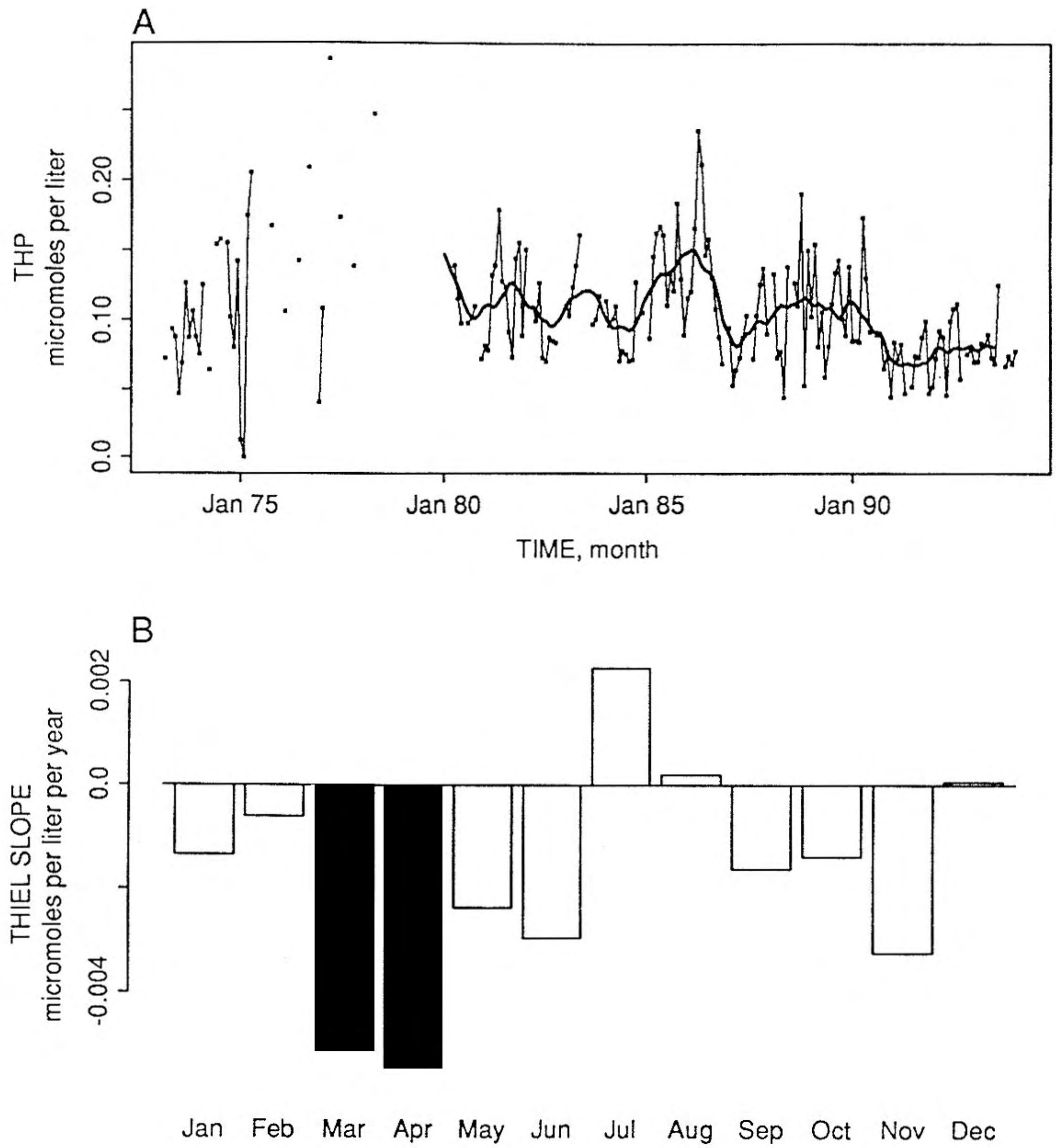


Figure 4-40—As in Figure 4-39, except for total hydrolyzable phosphorus. Thiel slopes indicate a reduction in THP concentrations over the period of record (from Jassby et al. 1995).

THP show only weak evidence for a long-term change in lake water chemistry? Jassby et al. (1995) offer a number of possible explanations.

First, NO_3^- and THP may not represent the total biologically available N and P pools. If this were the case, a change in bioavailable N or P could occur and affect lake response but still not be reflected in the NO_3^- and THP series. The bioassay data (see discussion above) indirectly suggest such a lack in correspondence between the measured NO_3^- and THP series and the true biologically available pools. Despite the large interannual variability in NO_3^- and THP, P-limitation has been remarkably consistent since about 1982, indicating a more stable supply of bioavailable N and P than implied by the time series measurements.

Second, it is possible for increased loading to induce an increase in primary productivity with no significant change in the concentration of dissolved nutrients. Studies of P-cycling within the open water regions of lakes indicate that phosphate is very rapidly incorporated into phytoplankton and bacteria (Lean 1973). The dynamic movement of P among phosphate ($PO4^{-3}$), particulate-P (algae), low molecular weight-P and colloidal-P affects the pool of bioavailable-P. Phosphate uptake and turnover has been found to be extremely rapid during times of high demand (active algal growth) and low loading inputs. During these periods, newly loaded $PO4^{-3}$ is likely to be consumed within a period of minutes to just a few hours at most (Wetzel 1983). Phosphate turnover is more rapid under oligotrophic conditions where P-deficiency exists (Peters 1979), e.g., Lake Tahoe. P-cycling in lakes is regulated not only by biological transformations but by abiotic processes, such as complexation or dissolution from inorganic particulate matter (e.g., eroded soils). Monitoring and research efforts on the P-content of Lake Tahoe or P-inputs have not focused on the question of bioavailability; however, given that TRP was 84 percent of the whole-lake THP pool in 1992/1993 but only 45 percent and 41 percent of the TOP and TP pools, respectively, a large portion of lake THP may be bioavailable. As a consequence of its potentially rapid turnover, THP would not be expected to accumulate over time. Clearly, the understanding of lake response to nutrient loading requires a much more thorough understanding of P and N bioavailability, both as a function of loading and the nutrient reservoirs in Lake Tahoe.

A third possible explanation for the apparent lack of a long-term change in water chemistry despite a clear signal in lake response is that trends in nitrate and THP could be disguised by the strong interannual variability and that measurements are too near the analytical limits of detection. Jassby et al. (1995) point out that the whole-lake nitrate pool during summer stratification (June through August) is, on average, about 20 percent lower during years of deep spring mixing. Deep mixing occurs on the average of once in three years, during which time nitrates and other nutrients released by decomposition in deep waters are delivered to the euphotic zone where they can be taken up by phytoplankton. While this process does not affect whole-lake TN, it will change whole-lake $NO3^-$. Jassby et al. (1995) calculated that the difference in $NO3^-$ during summer stratification between deep- and shallow-mixed years is on the order of 3 μg N/L but that a $NO3^-$ increase of only half that amount (1.4 μg N/L) hypothetically could result in a whole-lake doubling of phytoplankton. Given that the analytical reporting limit for nitrate is approximately 1 μg N/L, long-term changes in Lake Tahoe phytoplankton may not be readily discerned from the nitrate reservoir, despite the fact that nitrate is readily bioavailable. Similar concerns exist for phosphorus in Lake Tahoe.

Fourth, in the most recent analysis of the origin and scale dependence of temporal variability in Secchi depth transparency in Lake Tahoe, Jassby et al. (1999) suggest that mineral suspensoids from eroded watershed materials may contribute to the documented decline in lake clarity. To the extent that these materials contribute to the decline in Secchi depth, the relationship between THP and $NO3^-$ will not be unambiguous.

Finally, the possible downward trend in THP suggested by the post-1979 time series, while intriguing, should not be overinterpreted. While it could be argued that erosion control measures in the Tahoe basin over the past 20-plus years have had an effect on P-loading, the observed trend in THP (arguably, more closely related to soluble-P than total-P) also could be the result of increased phytoplankton uptake of lake-P, which would result from the continued atmospheric deposition of nitrogen directly to the lake surface. Indeed, this would be consistent with algal bioassay results that show an enhanced response to additions of N and P simultaneously and with the observed increase in primary productivity of Lake Tahoe.

Changes in Lake Nutrient Content

Mass Balance Considerations—For the reasons presented above, evaluation of the long-term nitrate and THP series may not yet be adequate for the purpose of determining long-term change in the nutrient content of Lake Tahoe. Using the 1992/1993 estimates of lake nutrient pools and applying a mass balance approach (change in lake nutrient content = inputs/outputs), Jassby et al. (1995) addressed the question: Are estimates of the doubling times for TN and TP pools compatible with the time course of measured change in Lake Tahoe's primary productivity and nutrient limitation; that is, in order for nutrient loading from atmospheric deposition and watershed runoff to drive the changes seen in lake response from the instrument record, the TN pool must have changed significantly during the past 30 years.

Taking nitrogen (N) as an example, mass balance for TN in lake water requires that:

$$\frac{\partial N}{\partial t} = \frac{LN}{H} - (r + sN)N$$

where:
$\frac{\partial N}{\partial t}$ = change in TN over time
N = average whole-lake concentration (mg/m^3)
LN = external loading rate (mg $N/m^2/yr$)
H = mean depth (m)
r = flushing rate constant (1/yr)
sN = rate constant for loss other than outflow (1/yr)

Based on studies of nutrient loss rates at other lakes, the doubling time for the TN pool was estimated as 52 years; the calculated lower limit was 30 to 35 years. These values are consistent with the time scale of change in the record for primary productivity. In other words, at current rates of TN loading, lake content can double on the time scale of three to five decades. It is noteworthy that in the absence of atmospheric TN loading, the TN doubling time would have been much slower, at 220 years. Doubling time for the TN:TP ratio in Lake Tahoe is on a similar time scale, or 30 years (Jassby et al. 1995).

What is the magnitude of nutrient loss from Lake Tahoe and what is the importance of loss processes on mass balance and nutrient accumulation?

Mechanistic water quality models and nutrient budgets are based on the principle of mass conservation. By definition, therefore, one would expect that mass balance equations balance when all terms for the nutrient pools, sources, and sinks have been correctly specified. Unfortunately, it is often impractical or cost prohibitive to measure each of these terms individually for any particular system. Therefore, at least one term generally is specified in the mass balance equation by forcing a fit to the equation or by extracting a coefficient value from cross-sectional studies, where data from a spectrum of cases (lakes) have been analyzed for a general empirical specification of the relevant parameter or coefficient.

Clearly, accurate specification of nutrient loss coefficients is an essential step in the construction of mass balance models that are used to better understand a system and its response to mitigation. Most easily measured of these loss coefficients are the nutrient outflows that occur with hydraulic discharge. Other nutrient loss processes, however, may be more important; especially when the system has a long hydraulic residence time. At Lake Tahoe the hydraulic residence time is about 650 years (Marjanovic 1989). Data on nutrient loss from surface discharge to the Truckee River indicate that flow out of the lake represents less than five percent of total nutrient loss. Loss of nitrogen resulting from denitrification was measured in a preliminary fashion in the early 1980s. Because of the extremely low concentration of nitrate in the sediment porewater, rates were below detection in unamended samples.

Accurate specification of the sedimentary loss rate, therefore, is a critical parameter for mass balance models of Lake Tahoe. The coefficient of sedimentary loss can be expressed as a sedimentation coefficient, σ (Vollenweider 1969, 1975), as a settling velocity, v_s (Chapra 1975), or as a retention coefficient, *R* (Dillon and Rigler 1974). Although these coefficients are not easily measured directly, their general values and some criteria for specification have been derived from empirical relationships observed in several cross-sectional studies. The coefficients also are intrinsically related (Chapra 1975), so they can be converted from one form to another within a specific system, depending on the data available and the question at hand.

At Lake Tahoe, Heyvaert (unpublished) recently has measured nutrient settling velocities (v_s) for phosphorus from the accumulation rates in several mid-lake sediment traps, according to the equation:

$$v_s = J / P$$

where:
J = downward flux of phosphorus to the sediment (mg m^{-2} y^{-1})
P = lake phosphorus concentration (mg m^{-3})

Values for this coefficient were directly determined from two distinct hydrologic periods in recent lake history, thereby representing a range of values likely to be encountered within this system. The phosphorus settling velocity for a two-year period during the drought of 1987 to 1994 was 10.3 m y^{-1}. During the post-drought interval from 1995/1996 this coefficient was 22.5 m y^{-1}. The long-term average is likely to be some intermediate value, which is defined at this time simply as the mean (16.4 m y^{-1}). For Lake Tahoe, with a mean depth of 313 m and a maximum depth of about 500 meters, the phosphorus settling time to these depths would be on the order of 19 years to 31 years, respectively.

These results compare favorably to coefficient values derived from several commonly cited cross-sectional studies. In one analysis from the Canadian Shield Lakes, for example, Chapra (1975) found the best empirical fit to phosphorus retention data was provided by a phosphorus settling velocity of 16 m y^{-1}. This is remarkably similar to the estimate from Lake Tahoe. Other cross-sectional studies have reported somewhat lower values. Larsen and Mercier (1976) fit a phosphorus settling velocity of 11.7 m y^{-1} to data from a similar study but with a different set of lakes. DePalma et al. (1979) found that literature values reported for this coefficient ranged from 0.7 to 37.9 m y^{-1}, with a mean of 9.5 m y^{-1} among 50 temperate lakes. Results from Lake Tahoe fall within this range, although somewhat above the typical average. While the downward flux of phosphorus at Lake Tahoe may be relatively efficient, compared to other systems, its overall settling time is longer because of the great depth of this lake.

Assuming that the value for the coefficient of phosphorus settling velocity in Lake Tahoe is reasonable, it is possible to estimate a system response time to changes in phosphorus loading rates. Dillon and Rigler (1975), for example, suggested using a half-life time change, which is the time required to achieve a new concentration that is midway between the initial concentration and the final concentration, after a step decrease in loading. Based on the coefficient of phosphorus settling velocity (16.4 m y^{-1}) and some additional parameters describing the volume, depth, and hydraulic input rate for Lake Tahoe, the 50 percent response time to changes in phosphorus loading is about 13 years. Dillon and Rigler (1975) also suggested that three to five times the half-life, representing 87.5 to 96.9 percent of the time required to reach a final steady-state, could be used as a reasonable estimate for a lake's complete response. For phosphorus in Lake Tahoe this would be 39 to 65 years.

Although application of these sedimentation coefficients could be refined in a dynamic model of lake nutrient cycling, fundamentally the principle would remain the same, and results are likely to be quite similar. That is to say, a 50 percent phosphorus response time of between nine and 20 years is to be expected for Lake Tahoe, based on the range of coefficients obtained from sediment trap analyses to date. Similarly for nitrogen, a 50 percent response time of between 14 and 22 years is to be expected from nitrogen settling velocities of 9 and 15 m y^{-1}, measured during the drought and post-drought intervals, respectively.

Now, for the first time, it is possible to make an independent estimate of the annual nutrient loading necessary to sustain observed sedimentary loss rates. In this case, the sedimentary nutrient loss coefficients are applied to a mass balance equation, with the assumption that hydraulic outflow is the only other significant loss term for nutrients in Lake Tahoe (Jassby et al. 1995).

$$dc / dt = (W / V) - (Q / V)c - (v_s / H)c$$

where: c = lake concentration of nutrient (mmol m^{-3})
W = total loading of nutrient to lake (mmol y^{-1})
V = volume of lake (m^3)
Q = hydraulic input (m^3 y^{-1})
v_s = nutrient settling velocity (m y^{-1})
H = mean depth of lake (m)

Under steady-state conditions, this equation can be rearranged to yield:

$$W = cV(\rho + \sigma)$$

where: $\rho = Q / V$ = hydraulic flushing rate (y^{-1})

$\sigma = v_s / H$ = sedimentary loss coefficient (y^{-1})

For these calculations, the average lake nutrient concentrations were obtained from Jassby et al. (1995). Mean settling velocities for phosphorus and nitrogen were 16.4 and 12.0 m y^{-1}, respectively, as shown above. The volume of Lake Tahoe was taken as 156 km^3, with a flushing rate of 0.00154 y^{-1}.

Under these conditions, the annual lake loads necessary to sustain nutrient sedimentation losses are 401.7 metric tons N y^{-1} and 52.8 metric tons P y^{-1}, equivalent to areal loading rates of 57.3 and 3.4 mmol m^{-2} y^{-1} for nitrogen and phosphorus, respectively. These are both within about 10 to 20 percent of total annual loading rates calculated from the most recent nutrient budget for the lake presented at the beginning of this chapter. This relative congruence between independent methods is encouraging. However, the loading rates estimated from sedimentation velocities are greater than loading estimates from field measurements, which suggests that some nutrient sources in the budget may have been underestimated slightly. The inverse explanation, that nutrient sedimentation rates have been overestimated, seems unlikely since sediment trap data (0.25 m^2 and 0.5 m^2 baffled cones of Soutar oceanographic design) tend to underestimate the true sedimentation rates by 10 percent or more (Bloesch and Burns 1980). Natural variation in water column nutrient concentrations, as well as changes in the lake volume, hydraulic flushing rates or loading rates also could account for a portion of this small discrepancy. As discussed above, the current estimates of lake-wide N and P inputs are preliminary at this time; additional investigation is required, especially regarding the contribution of urban runoff.

As one final example of the potential benefit to be realized from this approach, a preliminary baseline phosphorus concentration for Lake Tahoe was calculated. This estimate is a hindcast of the long-term average predisturbance (prior to 1850) total water column phosphorus concentration, based on sediment core analyses and the phosphorus settling velocities. As derived from the previous equation for settling velocity:

$$P = J / v_s$$

Where J now represents the baseline flux of phosphorus, determined as the product of deep core sediment phosphorus concentrations and the average predisturbance mass sedimentation rate (Heyvaert 1998). This result is only as good as estimates for the flux term and the historical phosphorus settling coefficient, which is assumed to be equal to the average modern value. With those provisions, however, the results suggest that baseline concentrations would have been in the range of 3.9 ti 8.5 mg m^{-3}. Surprisingly, this is comparable to the 1992/1993 average whole-lake total phosphorus concentration of 6.3 mg m^{-3}. Perhaps small changes in the nutrient concentration of this historically ultra-oligotrophic lake cause big changes in its biomass, which are visible today. This is a reasonable hypothesis given that for every milligram of phosphorus used by algae in the formation of biomass, 41 mg of carbon are fixed and that small changes in particulate matter affect the relative clarity of oligotrophic waterbodies more than eutrophic waterbodies. In other words, the clarity of Lake Tahoe should be more sensitive to small changes in biomass relative to similar changes in a more productive lake.

In any case, the settling velocity is clearly a dynamic function for nutrients in Lake Tahoe. It may respond to changes in loading rates and matrix composition, as well as to shifts in relative nutrient concentration and to changes in lake biology. The continued joint analyses of whole lake nutrient concentrations and sedimentary loss rates will help define the nature of this function for Lake Tahoe and ultimately will improve models and their predictive accuracy for lake response to mitigation efforts and watershed restoration.

What has been the lake response during historical periods of disturbance and recovery?

Reconstructing Sedimentation Rates using Paleolimnological Techniques

Lake sediments constantly accumulate material derived from the watershed and from the overlying water column. Over time a physical record accrues. The biogeochemical analysis of this record can provide useful information about lake response to natural changes in environmental condition and to anthropogenic watershed disturbance. Sediment core analyses facilitate examination of ecosystem processes at longer and more relevant time scales than usually can be attained from any existing monitoring database. When used in conjunction with process-oriented research that includes both modeling and analyzing long-term data, this approach can significantly improve efforts to forecast ecosystem response to contemporary watershed disturbance. The following review comes from (Heyvaert 1998).

There have been two major episodes of watershed disturbance in the Tahoe basin since it was first located and described by John Fremont in 1844. The first event was clear-cut logging that began in the 1860s and continued into the 1890s; the second event was rapid urbanization in this watershed since the late 1950s. Of particular interest are effects on the lake function and its response to late 1800s logging in the Tahoe basin. This historical information could be instructive for evaluating modern environmental impacts from urbanization.

Over the years, several sediment cores have been extracted from various points within Lake Tahoe to determine spatial and long-term patterns of sediment composition and accumulation (Heyvaert 1998). These cores have been analyzed for many chemical and biological constituents and for characterization of their physical attributes. The specific goals of this project have been to identify biogeochemical markers that indicate lake and watershed response to ecological stress, to establish the baseline predisturbance condition of these markers and natural background variability, to assess watershed response to historical periods of fire, drought, and timber harvest, to determine lake response to urbanization since the late 1950s, and to establish a database for calibrating and verifying watershed-lake models in the Tahoe basin.

An early key step in this study was to establish a relatively reliable geochronology for the Tahoe sediments, constructed from ^{210}Pb and ^{14}C data. These data indicate that significant basin-wide changes have occurred in mass sedimentation rates over the last 150 years. Specifically, high sedimentation rates were associated with clear-cut logging in the Tahoe basin from 1860 to 1900, followed by a three-to five-fold decrease in mass sedimentation rates during the early twentieth century. These lower rates persisted until urbanization began in the Tahoe basin after World War II.

From ^{210}Pb data, the average mass sedimentation rate (with a 90 percent confidence interval) during the Comstock logging era from 1860 to 1900 was 0.043 (± 0.011) g cm^{-2} y^{-1}. By comparison, the average mass sedimentation rate for the recent period from 1970 to 1990 was 0.027 (± 0.006) g cm^{-2} y^{-1}. Both these rates are significantly higher than the average sedimentation rate of 0.009 (±0.004) g cm^{-2} y^{-1} that was determined for the intervening period from 1900 to 1970 (Table 4-6).

Predisturbance sedimentation rates were estimated from ^{14}C measurements in several deep sections of two cores. The long-term average rate was 0.006 (± 0.002) g cm^{-2} y^{-1}, which is slightly less than the sedimentation rate that was estimated for the intervening period between Comstock logging and urbanization. Because these rates are comparable, it would appear that landscape recovery was rapid after clear-cut logging ended and that sedimentation rates dropped to nearly predisturbance levels.

Reconstructing Historical Primary Productivity Rates

Diagenesis and organic decomposition preclude a quantitative reconstruction of historical primary productivity (PPr) from the carbon record. However, diatom frustules are composed of biogenic silica, which is relatively persistent in these sediments. Since diatoms represent greater than 80 percent of phytoplankton biomass in Lake Tahoe,

Table 4-6—The ^{210}Pb dates and sediment accumulative rates, with 90 percent confidence intervals, for Lake Tahoe sediment cores.

LT - Core	81-1	91-1	91-2	91-3	91-4	Mean	90% ±
Recent	1971	1969	1972	1973	1966	1970	2.5
(rate 1)	(.035)	(.026)	(.032)	(.021)	(.020)	(.027)	(.006)
Intervening	1901	1892	1901	1909	1902	1901	5.9
(rate 2)	(.007)	(.007)	(.012)	(.007)	(.014)	(.009)	(.004)
Historical	1864	1862	1878	1848	1854	1861	10.9
(rate 3)	(.060)	(.050)	(.042)	(.029)	(.035)	(.043)	(.011)
Baseline	LT-H-9	LT-91-1	--	--	--	<1850	--
(^{14}C rates)	(.009)	(.004)	--	--	--	(.006)	(.002)

Notes:
Mass sedimentation rates (g $cm^{-2}y^{-1}$).
Baseline sedimentation rates are from ^{14}C data.

the accumulation rate of biogenic silica should provide a useful proxy for algal productivity. Heyvaert (1998) calibrated the biogenic silica content of recent sediments to modern PPr measurements and then reconstructed PPr for premonitoring periods from the biogenic silica content of Lake Tahoe's historical sediment record. On average, this reconstructed PPr for the interval from 1900 to 1970 was 28 g C m^{-2} y^{-1}, which is about 25 percent less than the earliest ^{14}C PPr measurements conducted at Lake Tahoe in 1959 (39 g C m^{-2} y^{-1}). PPr reconstructed for the historic period of Comstock logging gave an average annual rate of about 176 g C m^{-2} y^{-1}, which is comparable to the annual average PPr measured in 1993 (183 g C m^{-2} y^{-1}). The estimate of baseline predisturbance PPr in Lake Tahoe before 1850 was 27 g C m^{-2} y^{-1}. Apparently, the lake nearly returned to this baseline PPr rate during the intervening period, after logging ended.

The fact that mass sedimentation rates and biogenic silica flux decreased shortly after the logging disturbance ended is testimony to rapid landscape stabilization with second growth forest. It also indicates that Comstock logging produced a pulse disturbance. By contrast, the disturbance from urbanization could persist as a chronic perturbation for considerable time. These data also suggest, however, that effective mitigation of the watershed erosion caused by urbanization could directly improve water quality over a relatively short period, probably on the order of about 20 years, plus or minus a decade. This corresponds to the 50 percent response times calculated independently from sediment trap data for nitrogen and phosphorus settling velocities.

At this time, the Tahoe basin sediment chronology and research estimates of mass and nutrient sedimentation rates continue to be refined. Work also has begun on the interpretation of additional sediment markers for understanding other disturbance patterns, including drought and forest fires, over longer baseline periods.

How does predictive modeling of lake response allow better strategies for restoration and management efforts at Lake Tahoe? What is the scientific basis behind the proposed TRG Clarity Model to be selected?

Role of Thresholds and Standards in Protecting Lake Tahoe Water Quality

TRPA currently has six water quality thresholds designed to protect the beneficial uses of Lake Tahoe. These are as follows:

- WQ-1—Shallow waters of Lake Tahoe (nearshore turbidity);
- WQ-2—Deep waters of Lake Tahoe (pelagic water clarity); includes WQ-2a, Capital Improvement Program, and WQ-2b, BMPs;

- WQ-3—Water quality (phytoplankton primary productivity);
- WQ-4—Tributaries (stream water nitrogen and phosphorus);
- WQ-5—Stormwater runoff quality (discharge to surface water); and
- WQ-6—Stormwater runoff quality (discharge to ground water).

Two of the most critical lake water quality thresholds, pelagic water clarity and phytoplankton primary productivity, are based on the historical database. The numeric value for clarity states that the average Secchi depth from December to March shall not be less than 33.4 meters. For phytoplankton growth, annual mean primary productivity shall not exceed 52 g $C/m^2/yr$. In both cases, these thresholds were not being achieved at the time they were established; however, in the spirit underlying the water quality standards sections of the federal Clean Water Act, the intended purpose was to set goals for desired water quality. For each of these parameters, threshold values represent levels measured from 1967 to 1971.

Numerical values for the tributary inflow and stormwater runoff thresholds are based on the Lake Tahoe Basin 208 Plan and the specific water quality criteria adopted by the states of Nevada and California under their water quality standards programs. For example, the numerical criteria or standards for surface water in the California portion of the Tahoe basin reflect historical (often pre-1975) conditions, and often the specific criterion is chosen so as not to exceed the 90^{th} percentile concentration. According the Lake Tahoe Basin Water Quality Plan, even if the standards set for the streams are achieved, further reductions in the nutrient concentrations in the stream may be required to prevent lake deterioration. Given that nutrients accumulate in Lake Tahoe for longer periods than in other lakes, (i.e., Lake Tahoe has an unusually long hydraulic and nutrient residence time) and that direct atmospheric deposition of nutrients to the lake surface and ground water discharge are important components of the nutrient budget, this assumption is not likely to be completely applicable.

Combined, the thresholds for the lake and surface runoff express the desire for lake clarity to return to the period from 1967 to 1971 when quality was significantly better. While this is an appropriate conceptual goal, and one that was warranted when the thresholds were first established in 1982, it no longer provides the most adequate framework for lake and watershed management in the next century. Within this simplified approach, the complex limnologic, hydrologic, biologic, and social factors that interact to affect lake clarity and water quality are not considered, vis-a-vis, specific management strategies. A considerable amount of research and monitoring has been completed since 1981; both the thresholds and future watershed policy require that this science-based knowledge be incorporated into the decision-making process.

In addition, the federal Clean Water Act requires states to develop TMDLs for impaired waterbodies. In concept, TMDLs are best viewed as watershed attainment strategies to ensure that water quality standards are attained. It is most likely that TMDLs, along with the state mandated TMDL implementation program will be critical in water quality plans, regulatory programs, and remedial plans and monitoring at Lake Tahoe.

For effective lake management, methods need to be established for answering the following:

1. What are the specific sources of sediment and nutrients to the lake and what are their respective contributions?
2. How much of a reduction in loading is necessary to achieve the desired thresholds and TMDLs for Lake Tahoe (i.e., lake response)?
3. How will this reduction be achieved?

Combined long-term research and monitoring in the Tahoe basin by a number of universities and agencies provided considerable information related to the first topic; in fact, much of this assessment is an attempt at an integrated presentation of this understanding. However, a number of critical pieces of information are still needed, and these areas are highlighted throughout this document. At the same time, TRPA's Capital Improvement Program, the wide range of interagency BMP and restoration projects (e.g., EIP), and other efforts in the basin are facilitating the conceptualize of factors that may be relevant to the third topic—how is a reduction of load achieved and which projects should be given priority. Indeed, while the EIP goes a long way toward identifying the needed restoration projects, this list is not complete. This issue is still far from being adequately understood well enough to implement the most ecologically and economically efficient management strategies. The second topic—how much of a reduction is required to achieve the desired thresholds—is critical but not known at this time. The TRG clarity model presented below attempts to address this issue in a quantitative and predictive manner.

Completion of watershed mitigation in the basin may take 10 to 15 years. Because the lake has such a long retention time for nutrients (decade time scale), the direct effect of this complete mitigation on lake clarity by monitoring alone will probably not be measurable for many years. Watershed and lake modeling provides an appropriate tool to overcome this long response time. Without this approach the results of watershed management actions today will not be known until much of the implementation resources are spent. With techniques that forecast the effect(s) of various management strategies on stream and lake water quality, the large amounts of financial resources and staff time that is anticipated for the Tahoe basin can be used in the most productive manner.

Need for a Watershed-based Lake Water Quality Model

Investigations from 1962 to the present have shown that multiple factors, such as the stress of land disturbance, habitat destruction, atmospheric pollution, erosion in disturbed watersheds, and extensive road network, have all interacted to degrade the basin's air quality, terrestrial landscape, and streams, as well as the lake itself. Inputs of nitrogen from atmospheric pollution and, in particular, accelerated erosion from natural and disturbed sections of the drainage, along with its associated phosphorus load, are considered major factors contributing to the decline of the lake's ecological health. Continued sediment and nutrient loading is a critical factor that reduces the long-term sustainability of this ecosystem (CTC 1987; Sierra Nevada Research Planning Team 1994; Jassby et al. 1994). Both water clarity and algal growth are parameters that reflect the long-term health of the lake; however, since their original adoption, neither threshold has been met, and no specific science-based tool exists for predicting the effect of current or proposed land use and watershed management policies on these parameters.

As human use in the basin increases, the effectiveness of natural pollutant control mechanisms, such as wetland and riparian treatment of runoff, ground water infiltration, and ground cover protection of erosion, has declined. Coupled with the well-documented increases in anthropogenic loading from the surrounding watershed and the atmosphere (Jassby et al. 1994) these conditions have led to artificially high nutrient and sediment delivery rates (Byron and Goldman 1989). Serious concerns about the ecological health and long-term sustainability underscore the urgent need to identify and conduct the highest quality science to link scientific understanding, policy, and watershed management. A critical component for long-term planning at Lake Tahoe is a water quality model, based on the lake's assimilative capacity to receive and process sediment and nutrients, which can be used to assess such future lake conditions as clarity. By knowing the level of loading required to return the lake to conditions defined in the thresholds, state standards, and TMDLs, responsible agencies will be better able to plan in a more quantitative and progressive manner.

The overall goal of the lake modeling effort is to link environmental policy and management in the basin to expected lake response. A clarity model for a Lake Tahoe model should define the relationship between land use in the surrounding watershed(s) and sediment/nutrient loading to the tributaries, between sediment/nutrient loading and algal growth, and between algal growth and sediment (silt) loading and clarity. By mathematically linking these variables (based on empirical data and limnologic and hydrologic principles) one can describe water clarity in terms of nutrient loading from both the watershed and atmosphere. Furthermore, the model should include a subcomponent that considers sources and transport of sediment and nutrients from both natural and urban activities in the watershed. The benefits to the TRPA and other basin agencies can be substantial. Ultimately such a model should be able to identify the total amount of nutrient loading per year required to achieve the Secchi depth threshold. Coupled with a nutrient budget, regulators can establish targets for reduction, which is precisely what is expected of a comprehensive TMDL program. Planning documents, proposed projects, BMPs, and restoration/erosion control work then could be assessed on the basis of their ability to meet these target loads.

Using Models to Predict Lake Water Quality

Water quality models are used both in diagnosing lake problems and in evaluating alternative solutions. The models define the cause-effect relationships that control water quality in quantitative or mathematical terms. Formulas used in these models typically come from limnological and hydrological theories and from literature case studies from other lakes. Much can be learned about Lake Tahoe by incorporating actual data from observations and studies of processes and responses in the lake. The long-term database for the lake and atmospheric deposition, coupled with the LTIMP database for many of the major tributaries, affords an invaluable background for these models. Because Lake Tahoe is unique in such qualities as its size and depth, mixing patterns, hydraulic residence time, nutrient cycling, biota, and subalpine watershed characteristics, dependence on theory or case studies from much smaller and shallower lakes is inadequate.

When used in the diagnostic mode, water quality models allow limnologists to assess what is going on in the lake, especially in reference to other similar waterbodies. At Lake Tahoe this is not of critical importance. Largely because of the long-term commitment to monitoring and evaluation, a good understanding of changes in Lake Tahoe and its tributaries exists. As discussed above, many of the symptoms of the on-going decline in lake water quality have been identified, and monitoring continues to assess trends. However, lake and watershed managers, environmental planners, and policy-makers need to know "what will happen to the lake if we do this, that, or the other thing" (US EPA 1988).

In the predictive mode, models can be used to forecast how lake water quality (or some particular aspect of water quality) will change in response to changes in nutrient loading or other controlling factors. Rarely do aquatic scientists have the ability to assess lake response based on whole-lake experimentation. And clearly, the purposeful addition of nutrients and sediment to Lake Tahoe to study its response threatens the very resource to be protected. While the combination of monitoring and research data allows a view of lake response over time, in the sense of a natural experiment, this approach is slow (only one new annual data point is added each year), it cannot be scientifically or statistically controlled (six consecutive years of drought provide little insight regarding lake response over a normal range of years), and the lake further degrades during the long observation process. However, models allow scientists to test hypotheses and various management scenarios and alternatives on the computer over a relatively short time scale.

Application of Published Models to Lake Tahoe

In the absence of a fully developed model at this time, and solely for the purpose of example (not for management decisions), some very basic and broad-based phosphorus loading model equations are being applied. These equations are empirically based, utilizing the observed mathematical relationships observed in a series of lakes. Often, these empirical models are regionally specific (Buiteveld 1995; Tilzer 1988). These models generally follow the framework that P-loading controls lake P-concentration, which in turn regulates chlorophyll or primary productivity and ultimately clarity. Application of these empirical models to Lake Tahoe is not advised for the purpose of strategic management planning. This is because Lake Tahoe is unique in terms of its very long hydrologic residence time, great depth, and oligotrophic nature, because phosphorus can be co-limiting with nitrogen at certain times of the year, and because fine inorganic sediment from the watershed also may be important in regulating clarity. When Lake Tahoe has been included in models of this type, it usually occupies a position on the outer edge of the relationship because of its relative pristine nature. Unfortunately, this is also the portion of the statistical regression curve where variation in the predicted parameter (e.g., chlorophyll and algal growth) is maximum. As discussed above, because the chlorophyll concentration is so low, even a relatively small variation could result in a 200 to 300 percent variation in lake response.

Used as an educational tool, however, these models can provide an order of magnitude estimate of lake response. For example, Vollenweider (1968) proposed a P-loading criterion in one of the first attempts to translate limnologic relationships regarding P-loading and lake chlorophyll into a form useful for lake quality management planning (Reckhow and Chapra 1983). Based on lake trophic status, P-loading ($g/m^2/yr$), and lake flushing for a wide cross-section of northern, temperate natural lakes, Vollenweider (1975) established P-loading criteria defined as permissible (oligotrophic) and dangerous (eutrophic). Using estimates for P-loading presented in the nutrient budget portion of this assessment, Lake Tahoe would be below but very close to the calculated permissible level.

Another example of using existing empirical models as guides is demonstrated by the very simple chlorophyll response model developed by Carlson (1977). Using a subset of northern temperate lakes, Carlson found the following relationship:

$$\text{Chl } (\mu g/L) = 0.068 \text{ P}^{1.46}$$

where P = lake TP concentration. Assuming a TP doubling time of approximately 40 years (based on discussion above related to nutrient mass balance), the lake concentration of TP could be expected to double (2X) by 2040 and triple (3X) by 2080, if inputs and outputs remain steady). If the current lake P-concentration is taken as 6 μg/L, Carlson's relationship would predict a 2.7-fold increase in chlorophyll by 2040 and a 4.9-fold increase by 2080, relative to current conditions. Further, Carlson's (1977) empirical model between chlorophyll and Secchi depth suggests that the 2.7-fold rise in chlorophyll could reduce Secchi transparency by a factor of 2; i.e., in 2040 Secchi clarity could be 50 percent of its current value. This first approximation is quite intriguing because the linear regression model based on the 30 years of Secchi depth measurements in Lake Tahoe predicts a 54 percent decline in Secchi depth by 2040.

Marjanovic (1989) used an empirical model developed by Smith (1982) that accounted for both nitrogen and phosphorus to predict Lake Tahoe chlorophyll. Marjanovic further combined this approach with a preliminary nutrient budget he developed for Lake Tahoe to evaluate a set of alternative N and P loading scenarios on the response of chlorophyll. While he stated that these analyses are qualitative only and should not be used as the basis for specific management policy, a number of suggestive conclusions are made. These include the following:

- Because nutrient loading to Lake Tahoe is only a small percentage of the total lake nutrient content, it will take many decades to discern the long-term effects of different management scenarios;
- A rapid implementation of measures to reduce nutrient loading may be a better alternative than slow stepwise nutrient loading control;
- Nutrient loading control strategies, while focusing on phosphorus, should not exclude the reduction of nitrogen inputs; and
- Accurate quantitative predictions of the fate of eutrophication in Lake Tahoe will be difficult; however, qualitative predictions of lake response based on different management and nutrient loading strategies are possible and should be sufficient for making sound and reasonable decisions.

In conclusion, a model of Lake Tahoe water clarity is needed as a tool to assist in watershed management. However, selection and naive use of an inappropriate model can lead to both unwarranted and unwanted results. Every lake is unique, and therefore each will respond to nutrient inputs in a slightly different manner. This is not to imply that lakes and their watersheds do not share certain features; indeed, the empirical lake response models described above attempt to exploit these areas of commonality. Scientists and planners alike must be aware of where the commonalty ends and uniqueness begins (Reckhow and Chapra 1983).

Simple application of any of the dozens of published empirical models or more complex process-based mechanistic models, which are focused on general applicability, will be of limited use at Lake Tahoe. Despite the fact that application of the Carlson (1977) equations to Lake Tahoe may yield "reasonable results," there are many such predictive equations in the literature (Buiteveld 1995). For many of the reasons previously stated—extreme depth and volume, long nutrient and hydrologic residence times, incomplete mixing from year to year, high susceptibility to atmospheric nutrient loading, proximity of many nutrient species to the analytical reporting limit—Lake Tahoe is more unique than common.

A number of factors contribute to uncertainty in quantitatively predicting the response of Lake Tahoe to management strategies to control nutrient loading. These include but are not necessarily limited to the following:

- Specific sources of nutrients and sediment to Lake Tahoe;
- BMP and restoration effectiveness;
- Proximity of many forms of N and P to the reporting limits;
- Biological availability of N and P both in the chemical sense of what organisms can utilize and the immediate fate of nutrient inputs;
- Relative contribution of organic (algae) and inorganic (watershed sediment) to lake clarity; and
- Effect of particle size on lake clarity.

As modeling efforts progress and as these models are fine-tuned, research and monitoring should be providing the answers to these and other questions.

Tahoe Research Group Clarity Model

The purpose of this model is to identify the total amount of nutrient and/or sediment loading per year required to achieve the Secchi depth threshold. Coupled with a nutrient budget, regulators then would establish targets for reduction. Planning documents, proposed projects, BMPs, and restoration/erosion control work then could be assessed on the basis of their ability to meet these target loads.

The overall conceptual framework for this model is presented in Figure 4-41; additional details will be incorporated as work continues. Water clarity or Secchi depth, is the primary response variable. This is reasonable given that thresholds for nutrients and primary productivity are all intended to stem the loss in transparency. In addition, given the importance of atmospheric deposition to nutrient loading at Lake Tahoe, this component will be considered.

Major model components include the following:

- Sediment, nutrient and water budgets;
- Sediment and nutrient loading-land use relationships;
- Nonpoint source pollutant transport model;
- Lake hydrodynamic and quality model; and
- Lake response model.

These components represent more focused models on their own. When mathematically linked into a larger more comprehensive model, they will provide new insight on predicted lake response based on various management and loading scenarios.

Model Components

Secchi depth is directly related to the amount and characteristics of suspended particulate matter (SPM) and, to some extent, of dissolved organic matter, in the upper portion of the lake's water column. In turn, SPM is composed of both living and dead organic matter (primarily from in-lake algal growth) and inorganic silt, which is transported from the watershed. Dissolved organic matter consists of humic substances from the watershed and breakdown products from algae. As shown in Figure 4-41, silt enters Lake Tahoe via surface runoff from tributaries and intervening areas and from direct on-lake deposition from the atmosphere. In addition, surface runoff and stream loading are regulated by climate and hydrology.

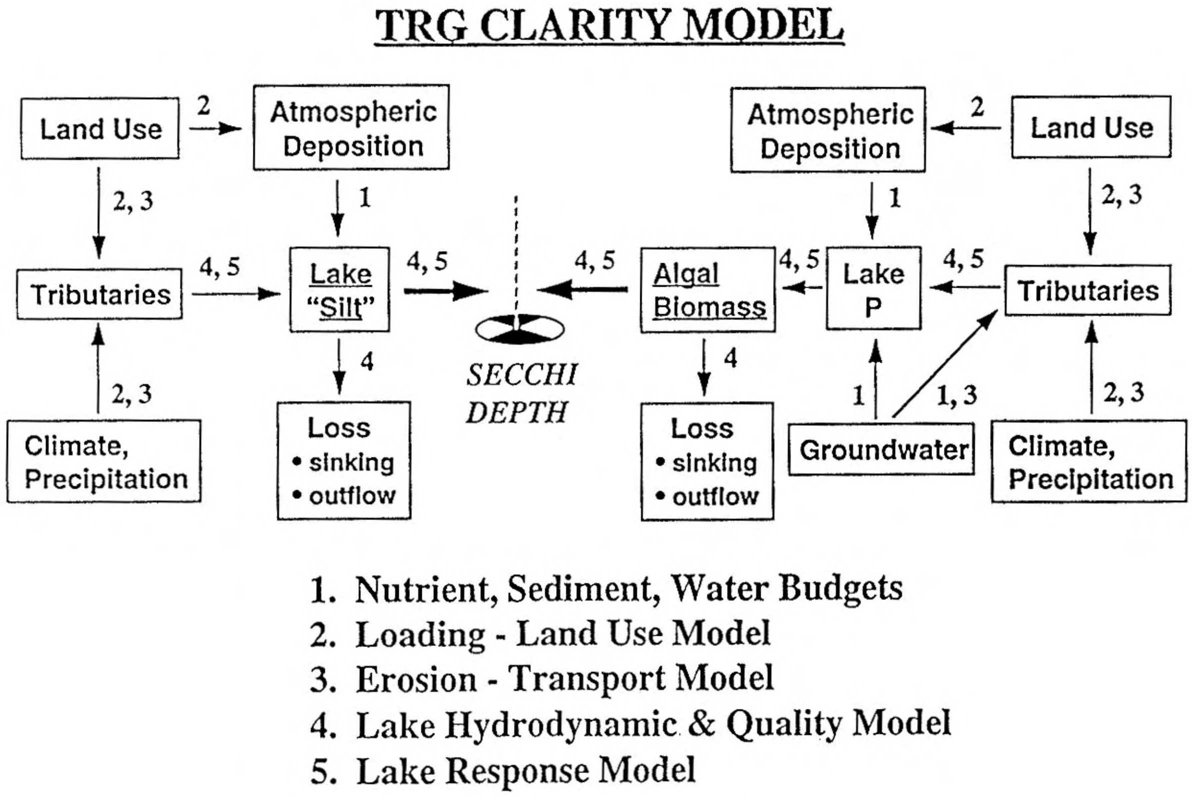


Figure 4-41—Conceptualization of TRG clarity model (from Reuter et al. 1998b).

The contribution of silt to the long-term decline in clarity has not received sufficient attention to determine its overall contribution to the loss of transparency. It is known that phosphorus loading to Lake Tahoe results from direct deposition of atmospheric fallout on the lake's surface and from surface runoff. The load associated with surface runoff again is dependent on land use and geomorphology. While silt can directly affect clarity as a result of an immediate increase in turbidity, phosphorus must first be incorporated into growing phytoplankton algae.

An important first step in lake modeling is to establish a water budget. Flows and direct precipitation carry sediment and nutrient into and out of lakes, and modeling efforts such as those described below require a quantitative understanding of lake hydrology. Not only does the amount of total precipitation affect sediment and nutrient loading, but the timing and conditions of rainfall and snowmelt also provide energy that contributes to the erosion and transport processes. Nutrient budgets identify sources of nutrients and sediments to lakes and define the balance between inputs and outputs. Given the conceptual model presented above for nutrient loading and algal growth, and assuming a steady state condition, lake quality would be expected in improve over time when outputs and inputs are balanced. The lake's assimilative capacity is exceeded at some point after inputs are greater than outputs. The proposed clarity model permits quantitative definitions of these relationships and to evaluate management alternatives that would lead toward a sediment and nutrient balance. A detailed sediment and nutrient budget also allow management policies to focus on the most important sources of these pollutants.

Understanding the relationships between land use in Tahoe's mountainous watersheds and the degradation of stream and surface runoff quality is an important component of effective watershed management policy. In order to predict loading, an understanding of how land use affects total phosphorus loading from both stream flow and surface runoff and from the atmosphere is needed. The sediment and nutrient loading/land use relationships address this in much the same way the TRG did in its evaluation of land use and water quality in Lake Tahoe tributary streams using only a four year database. Now that the LTIMP database has expanded to up to 19 years for some streams, this analysis will be extended and refined. The nonpoint source pollutant transport model applies a newly developed model, by the Department of Civil and Environmental Engineering at UC Davis, to describe the flow dynamics of nonpoint source pollutants over mountainous terrain. Simulation modeling of surface runoff, erosion, and transport of nonpoint source pollutants is a necessary approach in watershed assessment research.

The lake hydrodynamic and quality model employs an existing limnological model to determine the interactions among suspended particulate matter, chlorophyll, transparency and the physical mixing environments in Lake Tahoe. This component of the overall model will make it possible to quantitatively explore the effects of a variety of watershed management strategies designed to reduce transport of sediment and nutrients to the lake. The lake response model is the important link between nutrient and sediment loading, and change in clarity. The relationships among nutrient (phosphorus) loading, lake concentration, primary productivity, chlorophyll, and transparency are mathematically determined in this component of the model. The lake response model also accounts for loss processes, such as sinking and deposition on the lake bottom, outflow, and zooplankton grazing in the case of algal biomass.

In concert, these components will allow TRPA and other basin agencies to assess watershed and lake management alternatives on water clarity. As with all models, calibration and verification will be part of the effort. Additional background information on the nonpoint source pollutant transport model, lake hydrodynamic model, and lake response model is necessary.

Simulation modeling of surface runoff and erosion and transport of nonpoint source pollutants is a necessary component in watershed and lake water quality models. Along with estimates of atmospheric deposition and ground water flow, the Nonpoint Source Transport Model not only will be used to assess differences in various watershed management alternatives, it also will supply loading data for the Lake Hydrodynamic and Quality Model and the Lake Response Model. Despite the recent availability of models intended to predict watershed behavior, their applicability to the complex, mountainous landscapes of the Tahoe basin is questionable. Consideration of landscape complexity in mountainous environments at multiple scales (i.e., < 50 m x 50 m, hundreds of hectares, many square kilometers) becomes fundamental in evaluating alternative strategies within an integrated watershed context.

The nonpoint source pollutant transport model described in this section is a mechanistic model that utilizes a new technique developed by faculty in the Department of Civil and Environmental Engineering at UC Davis (Dr. M. Levant Kavvas and collaborators). When used as part of the overall TRG Clarity Model, this component will be applied at the subwatershed and watershed levels. Based on a wide variety of watershed characteristics, including weather, microtopography, and urbanization, the results of this model will provide input data on sediment and nutrient loading to the lake. These data subsequently will be incorporated into the Lake Hydrodynamic and Quality Model and the Lake Response Model. The versatility of this model is that land use alternatives, including development scenarios and BMP mitigations, can be quantitatively evaluated for effects on loading.

Historically, erosion and runoff estimates have been predicted for agricultural areas using empirically derived equations, including the Universal Soil Loss Equation and the SCS curve number method (ARS, USDA 1965). More recent approaches consider continuity equations for such components as water conservation and sediment (Foster 1982). The approximation of hillslopes by kinematic cascades was one of the first successful attempts to consider landscape features in combination with a physical-based approach (Woolhiser et al. 1990). Although the large number of commercially available erosion and nutrient transport models, such as AGNPS, ANSWERS, CREAMS, EPIC, EUROSEM, KINEROS, SHESED/SHETRAN, SWAM, and WEPP, have significantly improved knowledge regarding the process of soil erosion, they have limitations and deficiencies that restrict their practical use in locations with highly variable surface structures.

These limitations include the following:

- The use of point-scale equations to describe spatially occurring processes requires too many simplifications to maintain the applicability of the overall model;
- Due to high spatial variations of the hillslope topography, the assumptions of gradually varied flow in the currently utilized point-scale technology do not hold unless one smoothes the important microtopographic flow controlling features;
- Quantitative input requirements (thousands of computational nodes) are very difficult to obtain; and
- The current point-scale technology considers conservation of mass and momentum only at the point-scale of a computational node and cannot account for mass/momentum conservation over the heterogeneous area that surrounds each node.

To overcome these deficiencies, Kavvas and co-workers introduced spatially averaged conservation equations into a newly developed hydrologic watershed modeling system with successful application at the hillslope scale (Kavvas and Govindaraju 1992). This modeling approach will be applied to the watershed scale to describe overland flow, soil erosion, and the transport of related sediment and nutrients.

On typical terrestrial landscapes, discharge occurs both in small-to-large channels or rills and as overland sheet flow. Most flow on hillslopes is found in rills; however, much of this flow comes from overland flow in interrill areas. The Nonpoint Source Pollutant Transport Model mathematically considers movement of overland flows and was derived from local averaging of the two-dimensional flow equations for sheet flow, based on the principles of mass and linear momentum conservation (Kavvas and Govindaraju 1992; Tayfur and Kavvas 1994). Combined rill (channel) and interrill (sheet) flows are treated in a single, spatially-averaged flow equation, with an additional flow interaction term (Govindaraju and Kavvas 1991, 1994a, 1994b). As natural surfaces have a large number of rills into which water flows from neighboring interrill areas, flow and sediment transport equations are averaged on a large-scale. Similar equations for overland transport of nutrients have been developed and applied by Kavvas and Govindaraju (1992). Using existing data on phosphorus/sediment relationship(s) in channelized flow (historic and ongoing stream monitoring) and overland flow (existing BMP monitoring database), watershed yield of this critical nutrient can be modeled.

The obtained combined rill flow-sheet flow equation and the averaged sediment transport equation, with their areal-average parameters and areal-average inputs enable the modeler to overcome the difficulties in estimating overland-flow and transport parameters. The Nonpoint Source Pollutant Transport Model is comprised of an interacting series of model subcomponents. As discussed above, the mathematical structure and computational framework have already been established. However, application of the model within the Tahoe basin requires collecting and incorporating a calibration data set for conditions in a selected watershed.

Calibration of each subcomponent requires quantitative estimates of the following components:

- *Overland flow*—areal averaged roughness coefficient both for rills and interrill surfaces, areal averaged bedslope both for rills and interrill surfaces and, rill cross-sectional geometry areal averaged dimensions;
- *Interrill area erosion/sediment transport*—areal averaged soil detachment rate from rainfall impact, mass density of the sediment, soil erodibility, critical shear stress for the interrill surfaces and, first order reaction coefficient for the computation of areal averaged soil detachment rate due to sheet flow;
- *Rill erosion/sediment transport*—first order reaction coefficient for the computation of areally averaged soil detachment rate, critical shear stress within rills, mass density of sediment particles, areal averaged dimensions of the rill geometry;

- *Stream flow*—bedslope, roughness coefficient, and dimensions for the stream channel;
- *Snowmelt*—snow depth, specific heat, density and thermal conductivity of snow cover, and snow albedo;
- *Stream sediment transport*—first order reaction rate for soil detachment from the stream bed, critical shear stress within the stream channel, mass density of sediment particles, and stream channel dimensions; and
- *Computation of phosphorus load*—requires the first-order kinetic coefficient that relates the sediment concentration to the phosphorus concentration.

After the calibration stage, the model will be validated on the basis of site-specific sampling in selected streams and the use of several historical events that were not considered during model calibration.

Once erosion, runoff, and other related hydrologic mechanisms in the watershed deliver sediment and nutrients to the inflowing tributaries and ultimately the lake, physical, chemical, and biological processes interact to determine its bioavailability and effect on clarity. The lake hydrodynamic and quality model will investigate the interaction(s) between ecological and hydrodynamic factors in the lake. The fate of organic (algae) and inorganic (silt) material in the water column is important when predicting the impact of this SPM on transparency. What is the residence time of the various forms of SPM within the upper waters where Secchi transparency is measured, and how does this change with season, year-to-year, and over longer periods? Existing research on rates of settling and changes in the chemical composition of this material (sediment trap data) will be used to validate this model. In addition, new research, which is providing direct measurement and characterization of inorganic and organic SPM at both a nearshore and pelagic station, allows for a direct determination of the biogeochemical nature of SPM and an assessment of its influence on long-term and seasonal changes in the lake's photic environment.

To understand the processes that control the temporal variability of transparency in Lake Tahoe, UCD will use an existing mechanistic dynamic, one-dimensional, process-based hydrodynamic model (Imberger et al. 1978), combined with a particle settling model (Casamitjana and Schladow 1993), and a set of submodels for phytoplankton production, dissolved oxygen, and nutrient cycling (Schladow 1998). This model, termed DLM (Dynamic Lake Model), allows accurate prediction of vertical temperature stratification without calibration. This means that the level of process description, including the temporal and spatial scales in the model, is fundamentally correct for situations where a one-dimensional description is appropriate (Patterson et al. 1984). The freedom from calibration allows identification of the specific hydrodynamic processes that influence water quality. This approach also enables the interactions between ecological and hydrodynamic processes to be examined at a more fundamental level because only the ecological component needs to be calibrated.

Preliminary numerical model runs using DLM have demonstrated excellent agreement with the measured temperature profiles in Lake Tahoe for three years (Schadlow unpublished). Despite its size and the complexities of the local meteorology, the lake's thermal structure was well represented as a one-dimensional system. Future model runs are expected to include the full 20- to 30-year historical record and to include previously developed algorithms for the settling of inorganic suspended particulate matter and chlorophyll production. The extremely long water quality record available for Lake Tahoe allows an extensive calibration and validation to be performed. Using this modeling approach, it also will be possible to quantitatively explore the effects of a variety of watershed management strategies designed to reduce sediment and nutrients being transported to the lake.

Once sediment and nutrient budgets are determined and characteristics of transport and loading are known, a lake response model can be used to evaluate existing conditions and to predict changes in phosphorus, chlorophyll, and transparency resulting from changes in phosphorus loading. The Lake Response Model can be used as a management tool to estimate total allowable phosphorus and fine inorganic particle loading to the lake (in the sense of a TMDL) or to predict water quality consequences of development and watershed management alternatives. However, it is important to keep in mind that for a lake as large as Lake Tahoe, no lake response model will be sensitive enough to predict the impact at the level of a new single-family dwelling. Because of the many uncertainties associated with a model of this large a scale, it is to be viewed as a management tool best used at the watershed and subwatershed level.

The framework for the typical phosphorus loading model used for northern temperate lakes is as follows (US EPA 1988):

Inflow	-->Phosphorus	-->Chlorophyll	-->Transparency (Secchi)
	(1)	(2)	(3)

This framework is based on limnological principles with the relationship between parameters defined in quantitative terms, using mathematical equations typically obtained from existing empirical models for other lakes. For example, estimates for step (1) above were presented in an early model by Vollenweider (1976), which related hydraulic residence time (lake volume÷outflow) and inflow total phosphorus concentration to predict lake concentrations. This model was intended to define the typical north temperate lake and indeed was based on data collected from dozens of systems. As discussed earlier, conditions at Lake Tahoe are unique and warrant the formulation of site-specific relationships for each of the processes above. When a site-specific clarity model is developed, both empirical and mechanistic features must be included. For example, the long-term loading and lake water quality data provide important answers in an assessment of lake response to sediment and nutrient loading. However, specific processes related to suspended particulate matter, such as zooplankton grazing, rates of sedimentation, decomposition and changes in biochemical composition, permanent burial on the bottom, and nutrient release from the sediment, will affect clarity. When important, these processes also must be incorporated into the overall model.

Figure 4-42 provides a simplified outline of the optical quality model. The DLM will provide values for organic and inorganic particle concentrations. These will be used to derive the inherent optical properties (light absorption and scattering characteristics) of the water. The results will, in turn, be used to calculate the overall light attenuation, appearance of the water, and the predicted Secchi depth.

What is the current status of macroflora (submerged aquatic plants) and macrofauna (benthic invertebrates, crayfish, zooplankton, and fish) in Lake Tahoe?

The current assemblage of macroflora and macrofauna in Lake Tahoe is largely the result of human influence in the Tahoe basin. Since Europeans began settling around the lakeshore, exotic species have been introduced both intentionally and accidentally. Many of the intentional introductions were planned by wildlife management agencies to increase the production of top predators for recreational harvest by the expanding human population. Species introduced accidentally is a common occurrence wherever human populations live in close proximity to recreational waterbodies. Plants and animals often are transferred from one location to another by trailered watercraft, either attached to the vessel itself or contained in bilge water.

The result of these introductions has been dramatic for Lake Tahoe. The historic native game fish, Lahontan cutthroat trout (*Oncorhynchus clarki henshawii)*, is no longer present within the confines of the lake. The only known location within the basin where the species exists is in a remote stream where strict management preserves a reintroduced population. This once great fishery produced many fish in the ten- to twenty-pound range and a record trout weighing 31 pounds. It was the introduction of an exotic predator, lake trout (*Salvelinus namaycush*), and human disruption of the native fish habitat that led to the species' demise in Lake Tahoe.

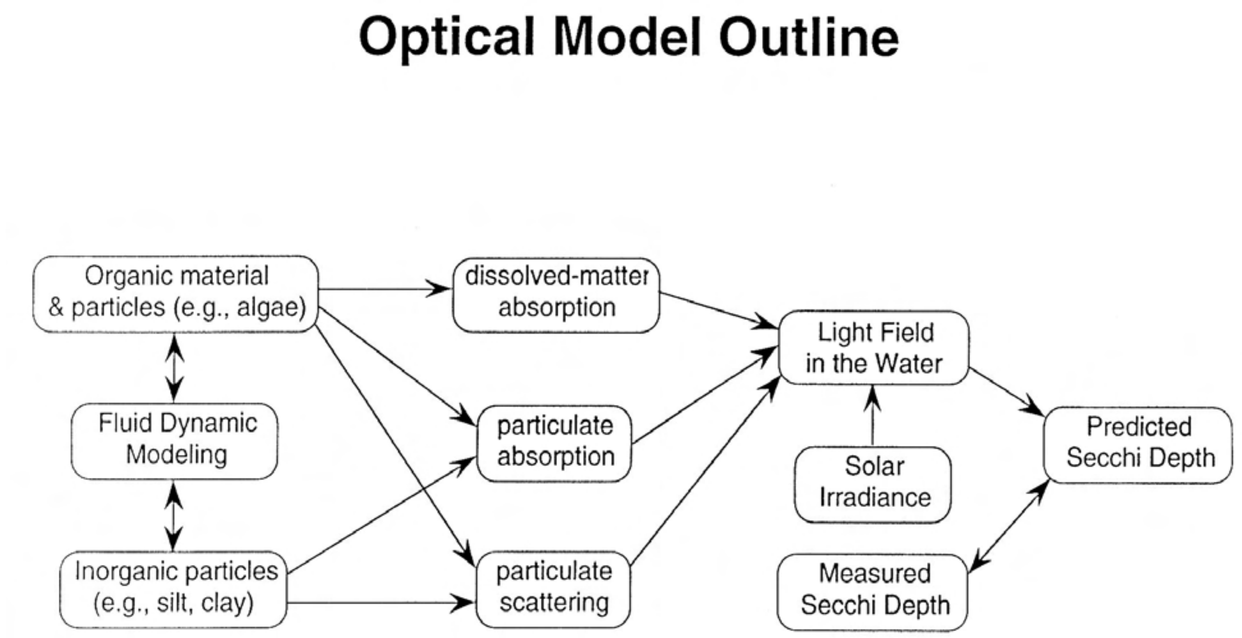


Figure 4-42—Conceptual model showing the relationship among material in Lake Tahoe, absorption and scattering of light, and Secchi depth.

The displacement of species was not limited to the fish community in Lake Tahoe. An intentionally introduced zooplankter (*Mysis relicta*) brought about the near elimination of three native zooplankters, *Daphnia rosea*, *D. pulicaria*, and *Bosmina longirostris*. These species remain weakly represented in the lake through seeding from other basin lakes via tributaries.

There are possibly other native species near extinction or that have gone extinct within Lake Tahoe as a result of exotic introductions or habitat degradation. However, without recent inventory studies, the status of much of Tahoe's macrobiotic populations remains unknown. It is clear that biotic introductions to the lake have greatly influenced the way the aquatic ecosystem functions. It is possible that in spite of well-intended efforts to increase Lake Tahoe's production of recreational species, the current assemblage is less efficient at energy transfer through the food web, resulting in a lower biomass of the top predators.

Current Assemblage of Macroflora in Lake Tahoe

While nutrient loading to Lake Tahoe continues to increase, many of these nutrients are stripped from the water column by the lake's phytoplankton, leading to the rapidly accelerating primary production rates. These same bioavailable nutrients therefore are not well transferred from the water column to the benthic milieu where they would be available to higher order aquatic plants. The only two areas in the lake where nutrients in the sediments can increase are the protected coves (both naturally occurring and human engineered) and the area below the zone of wave disturbance. Because Tahoe has a very steeply sloped littoral zone, there remains a relatively narrow area around the lake where plants might experience adequate nutrient levels in the sediments and a suitable sediment texture (fine silts) and still be shallow enough to receive the light intensity necessary for photosynthesis (Frantz and Cordone 1967). This was confirmed by a shorezone mapping project (Beauchamp et al. 1994b). During visual surveys, sand was found to be the most common substrate in the offshore zone, comprising over 80 percent of the habitat below 8 meters depth. Despite the lake's inhospitable conditions for colonization and growth, a diverse community of aquatic plants exists in the depths of Lake Tahoe. However, the greatest abundance of flora occurs in the shallow coves around the shoreline. These typically are associated with tributary inlets or marinas where sediments and nutrients accumulate.

Deep-water Plant Community

A study conducted during the 1960s included an inventory of Lake Tahoe's deep aquatic vegetation (Frantz and Cordone 1967) (Table 4-7). Plant collections did not produce any higher vascular plants but did reveal species of mosses, liverworts, and stoneworts. These plants were in greatest abundance between 61 and 107 meters deep, with a rapid decrease in density below 100 meters. Investigations into the health of the nonvascular macrophyte, *Chara delicatula*, collected from depth, found it to be exhibiting stress as a result of low light

Table 4-7—List of deepwater aquatic plants collected in Lake Tahoe, 1962 to 1963 (from Frantz and Cordone 1967).

Plant	Collection Depth
Green Algae	
Cladophora glomerata	194-411
Zoochlorella parasitica	127
Stoneworts	
Chara contraria	127
C. delicatula var. *annulata*	23-150
C. delicatula var. *barbata*	200
Yellow-green Algae	
Vaucheria sp.	175-362
Blue-green Algae	
Schizothrix calcicola	100
Mosses	
Fissidens adiantoides	244
F. granifrons	244-400
Brachythecium sp.	342
Eurhynchium sp.[1]	329-400
Hygrohypnum molle[1]	225-299
H. palustre[1]	290
Leptodictyum riparium	100-408
L. riparium forma *fluitans*	251
Porothamnium bigelovii	329-392
Fontinalis nitida	400
Liverworts	
Blepharostoma arachanoideum	329-362
Chiloscyphus fragilis	199-400

Note:
[1]Identification not certain.

levels. Tahoe's deep water plant species may suffer a loss of habitat, forcing communities shallower, as light penetration decreases in Lake Tahoe from further effects of cultural eutrophication. If shallower substrates (3 to 30 meters) outside embayments are not suitable for plant growth, as suggested above, species loss could be expected.

Link between Deep-water Hydrophytes and the Invertebrate Community

The agency study conducted in the 1960s also found a strong correlation between these deep plant communities and a variety of benthic invertebrates. Invertebrate samples collected within the plant zone showed densities an order of magnitude higher than those samples collected where plant material was not present (Frantz and Cordone 1996).

More recent investigations have found a connection between deep plant beds (*Chara delicatula*) and lake trout spawning (Beauchamp et al. 1992). Tahoe's top predator was utilizing the *Chara* as spawning substrate at a depth of 50 meters. Eggs were retained within the strands of *Chara* thus were protected from predatory juvenile lake trout. The study area was an underwater mountain and represented a refuge from other predators (crayfish) that would have less difficulty extracting eggs from the *Chara*. As a result, this area may be one of the most productive for lake trout recruitment. Further loss of lake clarity, resulting in decreased light transparency, could eliminate one of Tahoe's most productive spawning areas.

There are a few deep plant communities still existing in Lake Tahoe today, but the extent of their distribution is unknown. Further studies into the habitat requirements of these species and their link to the benthic invertebrate community would help managers predict future conditions based on water transparency models.

Shallow Plant Community

The shallow plant communities in Lake Tahoe were surveyed in 1995 to establish the extent of watermilfoil (*Myriophyllum* sp.) around the lake and to identify other plant species encountered (Anderson 1995). Eight species and their collection locations were identified (Table 4-8) in areas of stable nutrient-rich sediments, as discussed above.

Table 4-8—Shallow water plants collected from Lake Tahoe (from Anderson 1995).

Common Name	Scientific Name
Milfoil	*Myriophyllum spicatum*
Elodea	*Elodea canadensis*
Coontail	*Ceratophyllum desersum*
Spikerush	*Elocharis* sp.
Richardsons Pondweed	*Potamogeton* sp.
Horned Pondweed	*Zannichellia palustris*
Leafy Pondweed	
Chara	*Chara* sp.

Note: Plants were collected from the surface to a depth of 15 feet. Only common names were given in survey. Scientific names have been added for this text.

There appears to be little connection between the shallow vascular plant communities and the deep nonvascular plants described by Frantz and Cordone (1967). While the deep vegetative communities may be hindered by the increasing eutrophication of Lake Tahoe (decreased water transparency), the shallow plant communities could benefit.

Increased sediment load and nutrient-rich substrates accumulating in protected areas would favor the expansion of the shallow plant species.

Special attention should be given to the introduced Eurasian watermilfoil (*Myriophyllum spicatum*). This vascular macrophyte has demonstrated its ability to rapidly expand and eventually dominate the plant communities of other oligotrophic lakes. Watermilfoil propagates by seed, rhizome, and fragmentation, making the establishment of new communities readily possible. A single plant node can settle on suitable substrate and begin a new plant. Additionally, the seasonal senescence (growth phase from maturity to death) of the standing crop during winter helps bolster the organic content of the sediments for the following year's growth. This is an important advantage in Lake Tahoe, where much of the littoral zone is composed of coarse sand with a low organic content. Because watermilfoil grows to be quite tall, with a great density of stems, it is effective at decreasing water flow. This creates the potential for trapping sediments and further enhancing the plant community's prospects for expansion.

There is evidence that watermilfoil is increasing its distribution at Lake Tahoe (Anderson 1995). During the 1962/1963 study conducted by the California Department of Fish and Game and the Nevada Department of Wildlife, *Myriophyllum* sp. were identified in the shallow protected fringe of the lake (Frantz and Cordone 1967). While the propensity of this plant for rapid expansion raises concern, there does not appear to be the wide distribution at Lake Tahoe that might be expected, given the presence of *Myriophyllum*, for at least 25 years. Dr. Anderson and, separately, the Tahoe Research Group have observed propagules (plant fragments capable of regeneration) in the open lake. These propagules presumably would have established colonies along the open lake shoreline if substrate conditions were adequate. The lack of open lake watermilfoil communities may be due to the unstable, nutrient-poor sand substrate that dominates Tahoe's shallow (0 to 30 meter) shoreline.

Current Assemblage of Tahoe Macrofauna

The macrofauna of Lake Tahoe is composed of three primary communities, the benthic invertebrates, zooplankton, and fish. Much is known about the fish and zooplankton communities and the changes that have occurred at the hands of humans; however, Tahoe's benthic invertebrates have received relatively little study. Aside from an inventory list and some distribution data, virtually nothing is known about the ecology of the community.

Benthic Invertebrate Community

The most comprehensive information available on Lake Tahoe's benthic biota comes from a study that was completed by the early Frantz and Cordone work in 1963. Almost 400 bottom grab samples were collected from various locations and depths around the lake. The macrofauna from each grab were identified and used to make density and distribution estimates for Lake Tahoe. The following summarizes the findings of this study (Frantz and Cordone 1996).

The survey collected and identified 95 species from the bottom of the lake, representing seventeen major taxonomic groups (Table 4-9). Ten species were believed to be endemic to Lake Tahoe. It remains possible that some of these species also may have extant populations in other lakes in the Lahontan region. However, a lack of benthic invertebrate studies from other waterbodies does not allow for verification. There was a dramatic decrease in species diversity with increasing depth. Nearly 50 percent of the taxonomic groups were no longer present in samples below 150 meters. Oligochaetes numerically dominated the benthic invertebrate community and were collected from all depths sampled (5 to 500 meters). The calculated standing crop of all species of benthic invertebrates totaled 2,500 individuals/m^2 (6 g/m^2 wet weight), with oligochaetes comprising 40 percent by number and 65 percent by weight (Frantz and Cordone 1996). When compared to other North American oligotrophic lakes, the standing crop of benthic invertebrates was higher than eighteen of the twenty-one lakes listed. Based on Tahoe's low productivity and limited littoral zone, the abundant standing crop appears unique. The researchers conducting the study suggested that this may have been due to Lake Tahoe's lack of deep invertebrate predators, famed water clarity, and high dissolved oxygen concentrations throughout the water column.

The same study found relatively high densities of Tahoe's endemic wingless stoneflies (*Capnia lacustra*) between 60 and 90 meters deep, with 38/m^2 and 80/m^2 in 1962 and 1963, respectively. Later studies conducted in the mid-1980s, employing similar collection techniques, were not able to locate the deep living invertebrate (Nelson and Baumann 1989). Only a few individuals of this species have been collected since the original state agencies' study in the early 1960s. Specimens were collected in 1993 from a depth of 55 meters near Tahoe City (Allen unpublished). Efforts are underway to see if additional stoneflies can be collected from the deep waters of Lake Tahoe. Recent efforts have failed to capture any of the deep living stoneflies. *C. lacustra* serves as a good example of how little is known about Lake Tahoe's unique benthic organisms.

The most visible and perhaps best-known species in the benthic invertebrate community at Lake Tahoe is the signal crayfish (*Pacifastacus leniusculus*). It was first introduced to

Table 4-9—Macrobenthic organisms collected from Lake Tahoe, 1962-1963 (from Frantz and Cordone 1996).

Class: Tubellaria
Phagocata tahoena
Dendrocoelopsis hymanae

Class: Adenopherea
Cobbonchus pounamura
Hydromermis sp. or *Gastromermis* sp.
(or perhaps a new genus)

Class: Clitellata
Rhynchelmis rostrata
Kincaidiana freidris
Spirosperma beetoni
Limnodrilus hoffmeisteri
Varchaetadrilus minutus
Ilyodrilus frantzi typica
Rhyacodrilius brevidentatus
R. sodalis
Arctionais lomondi
Uncinais unicinata
Haplotaxis sp.

Class: Hirudinea
Helobdella stagnalis
Erpobdella punctata

Class: Crustacea
Latona setifera
Daphnia rosea
D. pulex
Simocephalus serrulatus
Bosmina longirostris
Drepanothrix dentala
Ilyocryptus acutifrons
Eurycercus lamellatus
Camptocercus rectirostris
Acroperus harpae
Alona quadrangularis
Pleuroxus denticulatus
Chydorus latus
C. sphaericus
Candona tahoensis
Epischura nevadensis
Leptodiaptomus tyrrelli
Acanthocyclops vernalis
Macrocyclops albidus
Hyalella azteca
Stygobromus tahoensis
S. lacicolus

Table 4-9—*(continued)*

Class: Arachnoidea
Lebertia sp.
Hydrovolzia sp.
Hygrobates sp.
Limnesia sp.
Piona sp.

Class: Insecta
Capnia lacustra
Utacapnia tahoensis
Nemoura sp.
Acroneuria sp.
Siphlonurus sp.
Callibaetis sp.
Centroptilum sp.
Heptagenia sp.
Choroterpes sp.
Paraleptophlebia packi
P. bicornuta
P. zayante
P. heinae (possibly new species as well)
Tricorythodes fallax
Gomphus kurilis
Hydroptila sp.
Limnephilus sp.
Hydroporus striatellus
Agabus disintegratus
Columbetes rugipennis
Tropisternus ellipticus
Laccobius ellipticus
Palpomyia sp.
Conchapelopia monilis
Apsectrotanypus (possibly *florens*)
Psilotanypus bellus
Pseudodiamesa pertinax
Monodiamesa bathyphila
Heterotrissocladius oliveri
Paratrichocladius sp.
Orthocladius obumbratus
Cryptochironomus near *fulvus*
Paracladopelma near *nais*
P. sp.
Polypedilum near *scalaenum*
P. near *parascalaenum*
Pseudochironomus pseudoviridus
Endochironomus near *nigricans*
Stictochironomus sp.

Table 4-9—*(continued)*

Phaenopsectra near *profusa*
Dicrotendipes near *modestus*
Cladotanytarsus sp. No. 1
C. sp. No. 1
Rheotanytarsus sp.
Tanytarsus sp.
T. near *guerlus*
Class: Pelecypoda
Pisidium sp.
Class: Gastropoda
Fossaria bulimoides
Physella virgata
Helisoma newberri
Vorticifex effusus
Ferrissia fragilis

the Tahoe basin in 1895 (Abrahamsson and Goldman 1970) as an early attempt to bolster the production of introduced game fish. The crayfish has become widespread throughout the littoral region of the lake, with mean density estimates of 10 individuals per square meter (Flint 1975). Crayfish have appeared in the stomachs of rainbow trout (*Oncorhyncus mykiss*), mountain whitefish (*Prosopium williamsoni)*, brown trout (*Salmo trutta*), and lake trout (*Salvelinus namaycush*) in Tahoe studies (TRG unpublished). While little is known about their importance to the other salmonid species, crayfish were calculated to represent over 13 percent of the annual lake trout diet by weight (Beauchamp et al. 1994c). It is unclear how well crayfish transfer biogenic energy to the lake trout population, but transfer is expected to be relatively inefficient due to the trout's difficulty in digesting and assimilating the crayfish carapace. The future for crayfish in Lake Tahoe appears to be sound. It is present in all habitat areas of the lake's littoral zone and has been observed to depths of 100 meters (TRG unpublished). While the crayfish are preyed upon by several fish species, birds, and various mammals, including humans, the population appears stable.

Flint (1975) conducted a study of crayfish life history in Lake Tahoe. He found that aquatic vegetation and attached algae made up over 65 percent of the adult crayfish diet. In controlled experiments in the lake, the ability of crayfish to depress the standing crop of aquatic macrophytes (*Myriophyllum* sp.) depended on the density of crayfish. Flint found that crayfish densities greater than 69 g/m^2 were capable of decreasing the standing crop of higher aquatic plants. Lower densities were found to stimulate vegetative growth.

Experiments were conducted in laboratory enclosures to determine if crayfish could effectively control the growth of Eurasian watermilfoil (*M. spicatum*). Initial experiments investigated the dietary preference of crayfish when exposed to three higher aquatic plant species from Lake Tahoe, *M. spicatum*, *Ranunculus aquatilis*, and *Elodea nuttalli*. Crayfish were found to feed on watermilfoil in the presence of the other species but selected watermilfoil second to *R. aquatilis* (Panayotou et al. 1996). During the experiment, grazing crayfish were observed creating floating propagules of watermilfoil. In order to ensure equal feeding opportunities on all plant species these propagules were collected daily and anchored to the bottom. In a lake situation, crayfish actually may promote the spread of watermilfoil by generating free-floating propagules.

During the lake trout spawning study, observations of *Chara delicatula* growth patterns were made. On the South Lake Tahoe mounds where spawning was confirmed, *Chara* grew to a height of 15 to 30 cm (Beauchamp et al. 1992). No crayfish were collected from this area, and it is suspected that the crayfish do not exist on the sea mounts because of the great depth from these mounts to the lake bottom (up to 105 meters). Therefore, *Chara* was able to grow in the absence of grazing. *Chara* on the shoreward slope in the vicinity of Camp Richardson Resort were found to have significantly reduced plant heights. Where *Chara* was observed above a depth of about 40 meters, plant height was estimated to be less than 10 cm. Taller plants were found at greater depths in the same location (TRG unpublished). Crayfish have been collected to depths of 100 meters in Lake Tahoe, but 90 percent of the population is found above 40 meters (Abrahamsson and Goldman 1970). Crayfish are suspected to be successful grazers on *Chara*, limiting overall plant height where the two species overlap.

Frantz and Cordone (1996) suggested that a lack of deep-living predators, the renowned water transparency, and high dissolved oxygen concentrations might be responsible for Tahoe's diverse and relatively high standing crop of benthic invertebrates. Since the comprehensive 1963 study (Frantz and Cordone 1996), the following changes have arisen that may have influenced Tahoe's benthic invertebrate community:

- The introduction of *Mysis* shrimp
- The decreasing water transparency due to cultural eutrophication; and
- The slow decrease in deep-water dissolved oxygen.

Prior to the introduction of *Mysis relicta* to Lake Tahoe, the species was thought to be a detritivore, feeding on organic matter on the lake bottom. While this scavenging strategy is utilized by mysids, they are also effective predators within the water column. Mysids have been shown to prey on amphipods and benthic cladocerans while on the bottom (as summarized by Northcoat 1991) and on other pelagic zooplankton species, including *Daphnia* sp. and *Bosmina* sp. (Threlkeld et al. 1980). It is unknown what effect the mysid introduction has had on Lake Tahoe's benthic community; however, the implications for species loss are strong. The 1963 benthic invertebrate survey discovered two deep-living endemic amphipods and referred to eight of the fifteen species of cladocerans as scarce (Frantz and Cordone 1996). These samples were taken prior to mysid abundance in the lake. If over the past thirty years mysids have been as successful preying on these benthic invertebrate species as they were on the pelagic species *Daphnia* and *Bosmina*, it is possible that several species have been eradicated from the lake. In fact, Frantz and Cordone (1996) state, "it is likely major changes in the Lake Tahoe macrobenthos have resulted from the combination of cultural eutrophication and the introduction of *M. relicta*."

The decreasing transparency of Lake Tahoe and its potential for limiting the deepwater plant community has been discussed above. This has important repercussions for the benthic invertebrate community as well. The California/Nevada study of the benthic community showed that a ten-fold increase in invertebrate density was associated with samples that contained plant fragments (Frantz and Cordone 1996). Investigations using a remotely operated underwater vehicle (ROV) and an occupied submersible found little benthic macroinvertebrate habitat, other than open silt, on the deep (> 60 m) lake bottom, except for a few isolated boulder escarpments (TRG unpublished). The primary structure associated with this profundal region of the lake is believed to be the plant communities. ROV surveys during lake trout spawning studies revealed only two deepwater plant locations (the South Lake Tahoe Mounts and lakeward of Camp Richardson Resort; Tahoe Research Group [TRG unpublished]). Efforts to revisit areas described by Frantz and Cordone (1967) failed to produce observations or collections of deep hydrophytes. The apparent attraction of these plant beds for benthic invertebrates creates an increased risk to their species diversity and abundance with decreasing water clarity.

The long-term record collected by the TRG has shown a slight, albeit steady, decrease in Lake Tahoe's dissolved oxygen concentration. While even the deepest lake waters remain saturated with oxygen year-round, the noticeable decrease warrants concern. It may be that the oxygen-rich deep water of Tahoe is partly responsible for the higher than expected standing crop of macrobenthos found by Frantz and Cordone (1996). If the trend toward decreased oxygen concentrations were to continue, further pressure would be put on the macrobenthic community.

Management strategies for preserving Tahoe's macrobenthos should include a detailed survey of the organisms present and continued efforts to halt the cultural eutrophication. Future studies designed to evaluate the macrobenthos should include sampling techniques that would allow comparisons to the data collected by Frantz and Cordone. It is important to know how species assemblages have changed over time and how the total standing crop has adjusted to the decline in water quality.

Macrozooplankton Species Composition

The crustacean plankton (zooplankton) community of Lake Tahoe and its environs has received a fair amount of study over the past three and a half decades. The Lake Tahoe plankton food web is discussed in Richards et al. (1991) (see Figure 4-43). Research into specific questions related to zooplankton ecology (e.g., life histories, community interactions, and population trends) has waxed and waned over the years, depending on research interest and funding availability.

Initial studies around the early part of this century were mainly short-term surveys (Ward 1904; Kemmerer et al. 1923) and were followed by a long period of almost no work until the late 1960s. Beginning with a doctoral thesis on the lake's plankton community structure and ecology (Richerson 1969), 15 years of zooplankton-related research has produced a half-dozen doctoral and masters theses and more than 20 peer-reviewed journal papers. Most of the work was completed by the mid-1980s, but a few papers were published on special projects as late as the early 1990s (Burgi et al. 1993). In addition to the zooplankton research, yearly and seasonal changes in populations have been monitored since 1967. Samples have been collected at the TRG's index station over 30 times annually since inception of the routine monitoring program. However, over the last 10 years, most of the collected samples have been simply archived for future analysis.

Because zooplankton sample counts and data analysis are so far in arrears, it is difficult at this time to determine whether significant changes in biomass, seasonal timing of population peaks and declines, or species composition have occurred. Zooplankton, as other living components of any ecosystem, can be indicator organisms, or early warning systems of impending or current change. This was illustrated by the changes that occurred in the zooplankton population (and subsequently are occurring in such other organisms as fish in the Tahoe food web) after the introduction of the

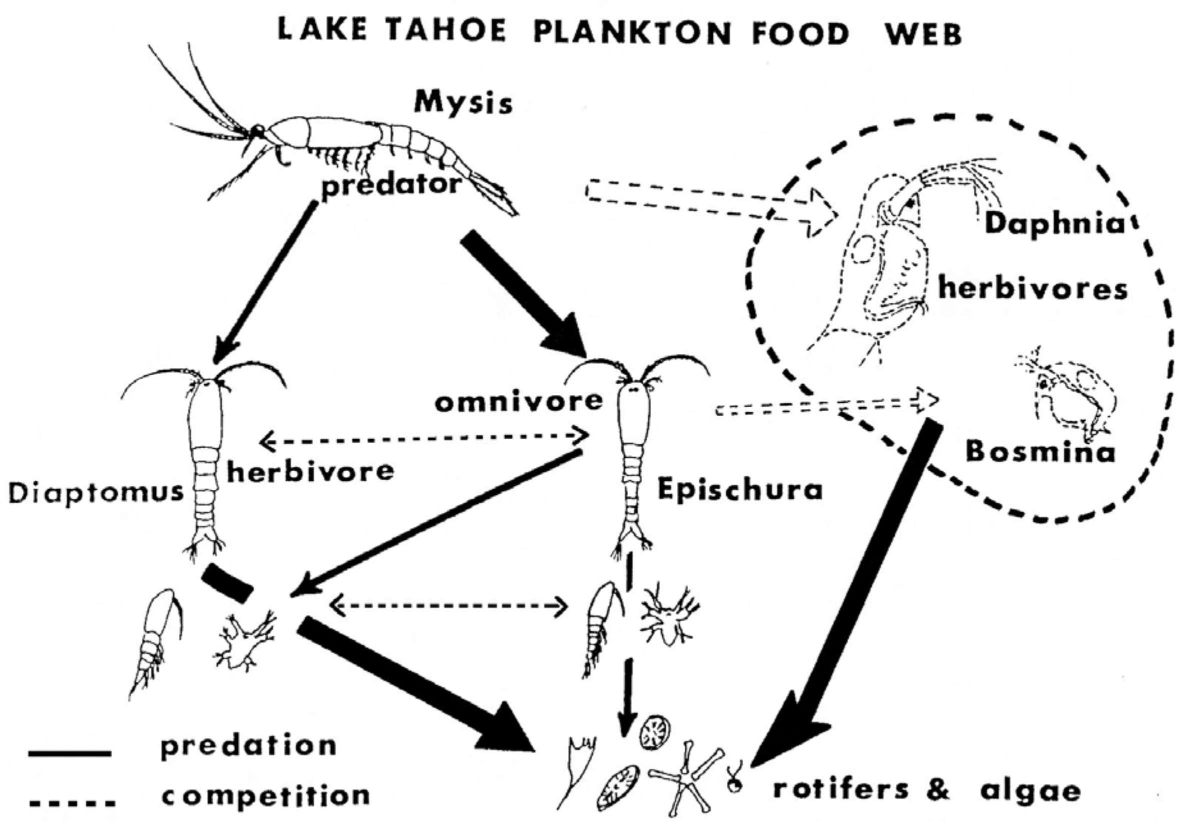


Figure 4-43—Lake Tahoe plankton food web (from Richards et al. 1991).

opossum shrimp, *Mysis relicta* in the early 1960s (Linn and Frantz 1965; Hansen 1966; Richards et al. 1975, 1991). Because of the sensitivity to change exhibited by this crustacean zooplankton and its importance within the food web as a major vehicle for transfer of energy from one trophic level to another (as a primary food source for fishes), it is advantageous to include them in future lake monitoring activities.

Since the analysis of the plankton community structure in 1969 by Richerson, much has changed to alter that community through the process of increasing lake eutrophication and other intentional or unintentional human-induced manipulations. Many fish and invertebrate species have been introduced, most with limited success. Undoubtedly, the most important recent introduction was that of the omnivorous opossum shrimp in the early 1960s by California and Nevada fish and game officials. *Mysis* was brought into the lake over a three-year period with the hope that it would supplement the food supply for kokanee and lake trout and that it would produce better sports fishing for the Tahoe angler. It was also introduced into many other waters in California and throughout the western United States.

This introduction was of limited success and was responsible for dramatically changing the makeup of the Lake Tahoe zooplankton food web (Richards et al. 1975; Morgan et al. 1978; Threlkeld et al. 1980; Morgan et al. 1981; Richards et al. 1991). This resulted from the lack of knowledge by zooplankton ecologists at that time in understanding the full dietary role of the shrimp in large and deep oligotrophic lakes and how shrimp behavior (e.g., diurnal vertical migration) modified their utilization by fishes. Incomplete life history information led to the premature introduction. While the introduction of this organism was successful in a few lakes, this was not true at Lake Tahoe. Although the shrimp was known to prey on other zooplankton, this role was underestimated for shrimp living in an infertile lake like Tahoe, where alternate food sources for such a large omnivorous invertebrate are limited (Sawyer 1985).

Fortunately, some of the highly affected species apparently have enough plasticity to rebound to some extent and make sporadic reappearances in the lake (Goldman et al. 1979; Threlkeld 1981; Byron et al. 1984, 1986). Additionally, it may have allowed for natural introductions of replacement or alternative zooplankton species into the lake's marginal environments, such as Tahoe Keys (Byron and Saunders 1981). Part of the ability of the major zooplankton species to respond to increasing predation rates by opossum shrimp lies in their varying capabilities for predator avoidance, their ability to remain in physical refuges, such as temperature barriers, or in geographical refuges, such as embayments, their adaptation to differing birthrates to keep pace with increased mortality, and their ability to maintain population densities relative to those of other available prey through competition mechanisms effective enough to ensure survival (Threlkeld 1979; Folt and Goldman 1981; Folt et al. 1982; Byron et al. 1986).

Many questions exist about the interactions among zooplankton, mysids, and the fish that depend on them for food. These questions provide a fertile field where much more research could be done to unravel relationships that are continuing to change in response to other environmental changes in progress in the Tahoe basin.

Much of the present status of the shrimp already has been covered in the previous section because its ecology is so interwoven with the smaller zooplankton species. Early research indicated that mysids were voracious predators on zooplankton (Rybock 1978) and that they were fully capable of causing near-extinction of prey species (Cooper and Goldman 1980, 1982) or at least effective in altering the zooplankton prey community composition more or less permanently (Folt et al. 1982). Indeed, the previously "simple" Lake Tahoe zooplankton community, which was dominated by four genera (two calanoid copepods [*Diaptomus* and *Epischura*] and two cladocerans [*Daphnia* and *Bosmina*]) before the mysid introduction has been simplified even further to a community dominated by only the two calanoid copepods (Figure 4-44).

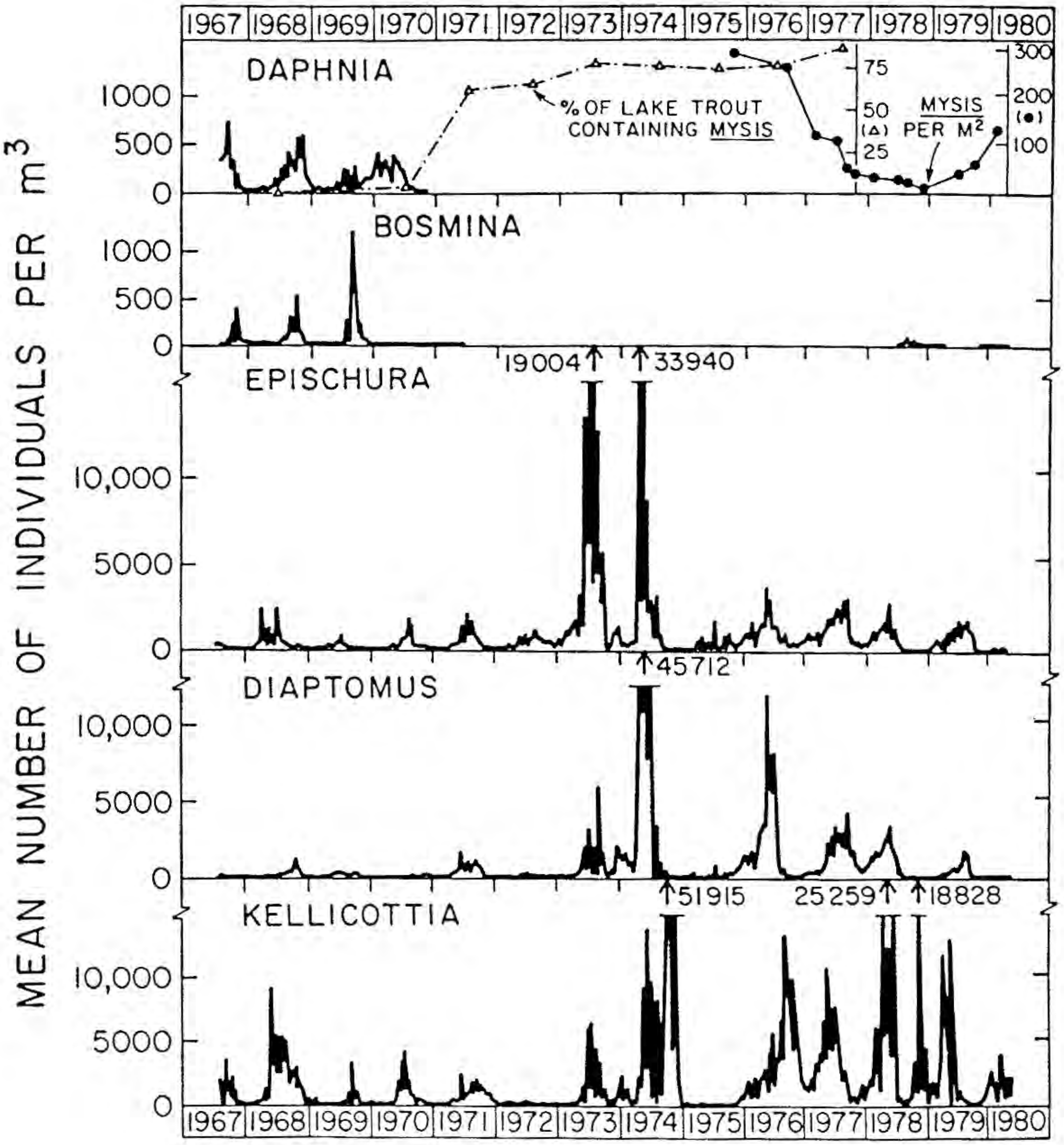


Figure 4-44—Change in Lake Tahoe zooplankton community following introduction of *Mysis* in the late 1960s (from Goldman 1981).

As with the zooplankton research and monitoring, emphasis has shifted away from intensive efforts to answer questions about how the shrimp are continuing to interact with and respond to the fluctuations in the Lake Tahoe environment. This decline in effort is unfortunate and should be remedied. A similar case could be made for including routine sampling for the opossum shrimp population at regular intervals because they also are good indicators of changing lake conditions and play a role not yet well understood in the transfer of energy through the food web from algae to fish. However, there is some speculation that *Mysis* might not be a very effective method of this transfer and actually are an ecological "bottleneck" for the flow of energy. Because of this unknown factor (which could be determined through appropriate research), opossum shrimp may or may not be a good indicator of change when considered as a potential environmental threshold species.

Up until the middle of the 1990s the TRG sampled mysids three to four times a year to characterize their population changes, despite a lack of funding or a directed program to document the annual and interannual trends. Recently, samples have been collected sporadically for other research purposes. Casual observations do show that an abundant number of shrimp are in the lake, and they do not appear to be fluctuating widely from population levels of the past.

Morgan et al. (1981) did a comparative study on the abundance, life history, and growth rates of the opossum shrimp in Donner Lake (outside the Tahoe basin) and Fallen Leaf Lake. In both lakes, mysids reached sexual maturity in one year due to higher fertility (greater algal production) than that found in Lake Tahoe, where maturity was at three to four years of age. Morgan also noted that these lakes exhibited algal growth rates similar to that found in Emerald Bay. During the period of study, Lake Tahoe was about a third as productive, with Secchi depth averaging nearly twice that of the other two lakes and the bay. Interestingly, although mysids were abundant in both these lakes in the 1970s, there was not nearly the total loss of the cladoceran zooplankton population as in Lake Tahoe. Emerald Bay, which has a fertility level similar to these lakes, maintains a coexistent population of the shrimp and the cladoceran *Bosmina* (Threlkeld et al. 1980).

Current Assemblage of Tahoe's Fish Community

The fish community in Lake Tahoe has received a great deal of attention for the past hundred years. Since early Europeans became year-round residents in the basin, humans have been attempting to enhance the productivity of Tahoe's top aquatic predators. These efforts have focused on introductions of exotic species near the top of the relatively short food chain. Despite repeated attempts, there is evidence that the production of top predators has actually decreased over time. The only certain product of human intervention in the lake ecosystem is a dramatically different assemblage of species.

Exotic Introductions

The introduction of exotic species to Lake Tahoe can be separated into three periods, 1875 to 1920, 1920 to 1965, and 1965 to the present. While the species and strategies varied during each period, the desired effect was always the same: find species that will increase Lake Tahoe's yield of game fish.

The Lahontan cutthroat trout (*Oncorhynchis clarki henshawii*) once dominated Lake Tahoe's waters and produced individual fish over twenty pounds within a thriving population. Due to human activities in the basin, which included logging, commercial fishing, water management practices, and exotic species introductions, the Lahontan cutthroat trout is no longer present in the lake. It has been replaced as the apex predator by lake trout, which were imported originally from the Great Lakes shortly before the turn of the 20th century (Dill 1997). The introduction of lake trout dealt the final blow to the already suffering cutthroat trout. Construction of Derby Dam in the lower reaches of the Truckee River and the dam at the outlet of Lake Tahoe in Tahoe City effectively cut off historic cutthroat migrations between Pyramid Lake and Lake Tahoe. This isolated the Tahoe population of cutthroat trout, requiring it to become self-sustaining entirely within the basin. At about the same time, clear-cut logging operations were causing heavy siltation in Lake Tahoe's tributary streams, making them unsuitable for cutthroat spawning. It is thought that this resulted in decreased recruitment to the isolated population. Commercial fishing for cutthroat trout continued all through this period. Adult fish were harvested for local consumption and were sent to markets in the Midwest. Around the turn of the 20th century, nearly 75,000 pounds of cutthroat trout were commercially harvested from Lake Tahoe (Roush 1987). The heavy fishing pressure significantly depleted the adult population in Lake Tahoe, reducing overall recruitment. The introduced lake trout are believed to have extirpated the dwindling cutthroat population by preying on many of the year classes remaining in the lake. Today's lake trout have been found to feed on individuals of the same species up to eighteen inches in length (TRG unpublished). This is the equivalent of about a two-pound fish, the size of the average cutthroat caught in Lake Tahoe in the early 1900s (Roush 1987).

Lake trout were only one of at least nine species of fish introduced to the lake between the late 1800s and about 1920. These introductions included chinook salmon, Atlantic salmon, golden trout, Arctic grayling, Great Lakes whitefish, brook trout, brown trout, and rainbow trout (Cordone 1986). In addition to the lake trout, brook trout, rainbow trout, and brown trout were able to establish self-sustaining populations either in the tributaries to Tahoe or in the lake itself. All other introduced fish species failed to thrive in the Tahoe environment. It was during this period that crayfish were introduced, presumably to provide forage for fish and for a growing human population. By the end of the 1920s Lake Tahoe's fishery was dominated by deepwater lake trout. A viable population of rainbow trout added to the recreational fishery. However, Lake Tahoe's vast volume and the pelagic nature of these fish resulted in a diluted population. The status of the native nongame fish in the lake during this period is unknown. It is believed to have been stable as all the species continue to have self-sustaining populations today.

A second series of introductions starting in the 1940s again were meant to increase the biomass of top predators. These attempts showed a shift in focus; rather than simply adding apex predators to the system, managers also introduced both zooplankton and lower trophic level fish.

The intentional introduction of *Mysis* shrimp from 1963 to 1965 (Linn 1965) resulted in the greatest change in the aquatic community since the loss of Lahontan cutthroat trout. The mysids established a thriving population by the end of decade (Goldman et al. 1979; Morgan et al. 1981). Their success was due largely to their exploitation of other zooplankton species, nearly eradicating three cladocerans from the system.

Kokanee salmon (*Oncorhyncus nerka*) were added to the lake in hopes of both providing forage for the piscivorous lake trout and of creating their own shallow recreational fishery. The recreational goal of this strategy was achieved initially, but it later was undermined by the expanding mysid population. Kokanee salmon is the land locked equivalent of the sockeye salmon. It has a four-year life cycle in Tahoe, growing from fry to adult in the open lake and feeding on zooplankton species. During the fall of their fourth year, adults return to spawn in the tributaries where they hatched. Both males and females stop feeding, undergo dramatic morphological changes, then spawn and die. In 1973 a California state record fish was caught, weighing just under five pounds. This phenomenal growth rate at Lake Tahoe was possible because kokanee were feeding on the then-abundant cladoceran populations in the pelagic regions of the lake. However, this success was short-lived because the mysid population soon began competing directly with the kokanee. By 1970/1971 (Goldman et al. 1979; Morgan et al. 1981), the mysids and kokanee had successfully depleted the lake of their preferred prey, *Daphnia rosea*, *D. pulicaria*, and *Bosmina longirostris*. The kokanee were unable to shift their diet to take advantage of the abundant mysids due to the mysid aphotic response. Mysids make a daily vertical migration away from light. This can be a descent of as much as 300 meters in Lake Tahoe (Rybock 1978), effectively removing them from the sight-feeding kokanee. The loss of the three zooplankton species mentioned above left two smaller more evasive zooplankton species, *Diaptomus tyrelli* and *Epischura nevadensis*, as the primary prey items for both kokanee and mysids. In a study of Lake Tahoe's kokanee, it was shown that individual kokanee size depended on the size of the population. This indicates that there is a limited food resource available within the lake (Beauchamp 1994a). It is unlikely, based on the current kokanee and mysid populations and their preference for *D. rosea*, *D. pulicaria*, and *B. longirostris* as prey, that these cladoceran species will ever regain strong populations within Lake Tahoe.

During this same period of introductions the California Department of Fish and Game and the Nevada Department of Wildlife attempted to reestablish populations of Lahontan cutthroat trout in Lake Tahoe. Three separate plantings of catchable size fish (> 20 cm estimated) were released into the lake between 1962 and 1965 (Dill 1997). Although the fish were marked prior to release, recapture efforts produced only about a one percent return. Within a few years the cutthroat trout had disappeared from Lake Tahoe once again. The state agency biologists concluded that the plantings of cutthroat trout had not been successful due to predation by lake trout.

The last series of exotic species introductions has been dominated by illegal introductions by individuals, presumably attempting to establish angling opportunities. Largemouth bass (*Macropterus salmoides*), smallmouth bass (*Micropterus dolomieui*), black crappie (*Pomoxis nigromaculatus*), and white crappie (*P. annularis*) all have been identified in the Tahoe Keys, a dredged harbor connected to Lake Tahoe (California Department of Fish and Game, unpublished observation, 1999). While all of these are considered warm water fish species and are expected to do poorly in Lake Tahoe's cold environment, there is evidence that even isolated populations could have significant impacts on the existing fish community.

Largemouth bass were first reported in the Tahoe Keys about twelve years ago. The highly productive, warm waters in the keys and the seasonally abundant aquatic vegetation (*Myriophyllum spicatum*) likely benefited all life stages of bass. As the population within the keys grew, bass began leaving the confined harbor. Fisheries investigations by the TRG in Taylor Creek, a tributary to Lake Tahoe, found summer resident bass. A survey conducted by fisheries biologists from UC Davis, TRPA, California Department of Fish and Game, and the Nevada Department of Wildlife identified largemouth bass during the summer in marinas at the north end of Lake Tahoe. Unless humans transported these fish, one can assume that the original population of bass from the Tahoe Keys has had the opportunity to occupy all suitable habitats around the lake. It appears that new populations of largemouth bass are locating in areas of the lake where they experience elevated summer water temperatures and aquatic vegetation. These areas are associated with marinas, large private piers, and creek mouths. While it is somewhat unlikely that largemouth bass will ever succeed in the open lake, even small, isolated populations of bass could have a dramatic effect on the current fish assemblage in Lake Tahoe.

A study of the ecology of nearshore fishes showed a correlation between rock crib piers in the Tahoe shorezone and increased fish density and diversity (Beauchamp et al. 1994b). Later work by Allen and Reuter (1996) demonstrated the attraction of spawning Lahontan redside shiners (*Richardsonius egregious*) to rock crib structures adjacent to shoreline spawning gravel. Because most marinas and large private piers are constructed of rock cribbing, there is an overlap of preferred bass habitat and habitat selected by aggregations of spawning nongame fish. The habitat preference of these species overlaps again at the mouths of Tahoe's tributaries. At least some portion of each of Tahoe's fish species, with the exception of lake trout, is known to utilize the tributary streams for spawning. The spatial overlap of a top predator (bass) and juvenile and adult prey species could have a devastating effect on the current fishery.

The eventual effect of having largemouth bass in Lake Tahoe is unknown; however, evidence suggests that even a limited distribution of these predators could eliminate one if not more of Tahoe's few remaining native fish species. A study assessing the potential for bass distribution and their impact on other fish species is strongly recommended. Control options for undesirable, nonnative fish species at the lake appear limited. There are strict prohibitions against the use of pesticides and herbicides within the Lake Tahoe basin. Mechanical methods of fish control (gillnets, traps, fishing) are not an effective means of reducing fish populations unless the fish are commercially valuable. Historical evidence indicates that the fish species humans place in Lake Tahoe will remain in the lake as long as they are able to establish self-sustaining populations.

Lake Tahoe's Trophic Cascade

The historic food chain in Lake Tahoe was very short and efficient. Phytoplankton were consumed by the grazing species of zooplankton, which fed the native minnows and subadult Lahontan cutthroat trout. Adult cutthroat ate the native minnows. There was a direct flow of energy through the system, with only three to four steps necessary to reach the apex predator. This allowed the cutthroat trout to achieve an exceptional biomass for the very limited production of Lake Tahoe.

It is ironic that all human attempts to increase the yield of top predators have most likely hampered the ability of resident fish populations to take advantage of the increased primary production that Lake Tahoe has experienced during the last three decades. Today the food chain in the lake is much less efficient than it was historically, with poor energy transfer between trophic levels. Primary production has increased three-fold in the past thirty years (Byron and Goldman 1986). Due to the loss of the historic zooplankton species *D. rosea*, *D. pulicaria*, and *B. longirostris* that were very efficient phytoplankton grazers, there is poor transfer of primary production to the zooplankton community. The remaining zooplankton species, *Diaptomus* and *Epischura*, being less efficient grazers, expend more energy while consuming the same amount of algae. It has been shown that these two species are more adept at avoiding predation than *Daphnia* and *Bosmina* were (Cooper and Goldman 1980). This implies that there is further energy loss today than within the historic food chain at the next trophic level. Native minnows and kokanee must expend more energy to capture the same amount of food energy in these zooplankton species. This is shown by the decreased kokanee size, which coincides with the loss of the original zooplankton assemblage (Beauchamp et al. 1994a).

The presence of mysids in the system further decreases the trophic efficiency. Mysids are a long-lived zooplankton species, requiring up to four years to reach adulthood (Morgan 1980). Also, they expend large amounts of energy maintaining their daily migratory strategy. Mysids may make daily vertical migrations of 300 meters to avoid light (Rybock 1978). This results in a 600-meter round-trip during every 24-hour period. Based on this consumptive life style, *Mysis* are expected to transfer very little energy from zooplankton prey to lake trout, which prey on *Mysis*. It has been suggested that lake trout are not able to control mysid biomass through predation (Beauchamp et al. 1994c). If this is the case, and mysids are high-level consumers of energy, they can be considered a bottleneck in the transfer of trophic energy.

Lake trout are a deepwater, bottom-oriented fish species. As adults, they are morphologically adapted to prey on fish with their widely spaced sharp teeth and short stubby gill rakers. Investigations at Lake Tahoe found that mysids dominated the lake trout diet during all seasons of the year for all sizes of lake trout (Beauchamp et al. 1994c). Because the species is not adapted to feed on zooplankton, it is probably relatively inefficient when feeding on mysids. This would be yet another trophic interaction that is expected to be less efficient than that which existed historically at Lake Tahoe.

Strong evidence exists that flow of energy through the food chain at Lake Tahoe today is very inefficient. Attempts to increase the yield of apex predators by introducing fish, zooplankton, and benthic invertebrate species probably have had the opposite effect. The current food chain is longer than that which existed historically, and the assemblage of species does not transfer energy efficiently due to limitations of life history strategies and morphological characteristics. Based on this information, it is not surprising that although Lake Tahoe has three times the primary productivity it did in the 1960s, there is no apparent increase in top predator biomass.

Management and Restoration Strategies for Tahoe's Macro Biota

Due to historical and recent exotic species introductions, there is little hope of the biological assemblage of species ever returning to native conditions. Reintroduced native species today would face dramatically different conditions in the lake and would not be expected to thrive as they once did. Plant species would face decreased light levels due to eutrophication, pressure from grazers, and competition for habitat from other introduced macrophytes. Reintroduced benthic invertebrates would face comparable difficulties, with lower dissolved oxygen concentrations and predation pressure from introduced species. Attempts by fish and game agencies to reestablish cutthroat trout in Lake Tahoe already have failed. These efforts were unsuccessful before mysids were fully established in the lake and before new fish predators (largemouth bass) were introduced.

Lake managers must therefore decide what species are desirable within the Tahoe basin and create strategies for their success. It is important to recognize that all nonnative species presently in the lake were desirable to somebody at some time. An optimal assemblage of species surely would inspire great debate among the scientific community, environmentalist groups, and private citizens. When and if this discussion occurs, special attention should be given to energy transfer through the food chain. Lake Tahoe continues to be an oligotrophic lake, with very low annual productivity. Anyone attempting to create thriving biotic populations needs to recognize that energy transfer between trophic levels is the limiting factor in a given species potential biomass.

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