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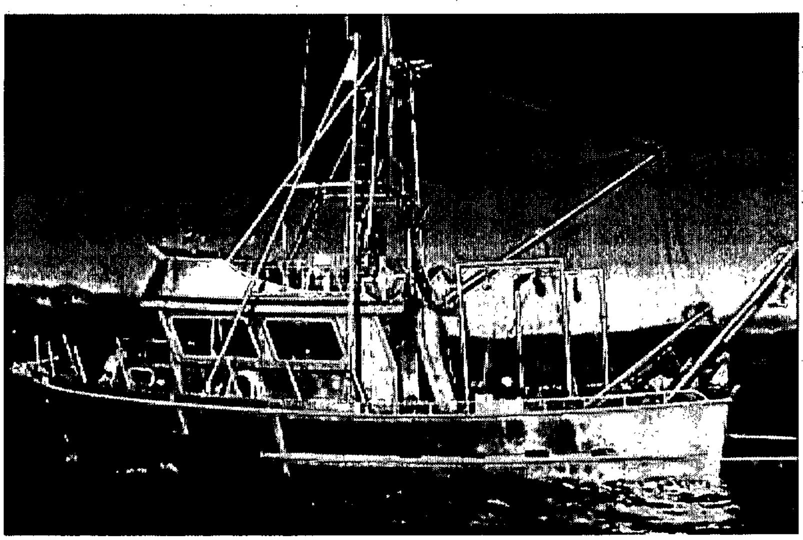
UCDAVIS TAHOE RESEARCH GROUP



ANNUAL PROGRESS REPORT - 2000

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WATER QUALITY, AIR QUALITY & FOREST HEALTH

Research, Monitoring and Modeling

Tahoe Research Group
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An Integrated Watershed Approach to Studying Ecosystem Health

at Lake Tahoe, CA-NV, USA

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Overview

Known for its beauty, remarkable transparency and cobalt blue color, Lake Tahoe, CA-NV is a natural jewel in the Sierra Nevada mountains. Its serves as the focus for millions of visitors annually and has international recognition. However, human development over the last five decades has been damaging. The lake has responded to increased nutrient loading, from streams, groundwater and urban runoff as well as atmospheric sources, with steadily increasing algal growth and a progressive reduction of clarity. The lake has lost over 10 meters (>30 feet) of transparency during the last 30 years and algal primary productivity has increased by approximately 5% annually over the same period. If allowed to continue unabated, the lake will lose its remarkable clarity and will likely experience a significant change in color in only 30 more years.

Urbanization has eliminated or damaged wetlands, wet meadows and riparian habitat, all crucial for natural water quality treatment. Forest health is significantly compromised with 25-30% of all trees either dead, dying or diseased. Aquatic biodiversity has been changed due to changes in environmental conditions and the introduction of exotic species. Air quality degradation is all too visible and atmospheric deposition directly to the lake surface has fundamentally changed the nutrient balance in the lake. New watershed management issues such as integrated erosion control, habitat restoration, and transportation are emerging as crucial to the lake's future. With the emerging consensus that the $1 billion annual tourist and recreation-based economy at Lake Tahoe, and the environmental concerns are linked, significant progress is being made to restore this fragile ecosystem. In a 1997 visit to Lake Tahoe, President Clinton and Vice-President Gore both stressed that long-term monitoring and a multidisciplinary research approach are essential as we move to restore this ecosystem. In this summary, we take an initial look at integrating a number of disciplines, all important to ecosystem heath and management at Lake Tahoe. These include air quality, water quality, forest health all affected by human development.

Environmental Setting

Lake Tahoe lies in the crest of the Sierra Nevada at an elevation of 1,898 m within both California and Nevada. The drainage area is 812 km2 with a lake surface of 501 km2, producing a ratio of only 1.6. The lake is located in a montane-subalpine watershed dominated by coniferous vegetation and nutrient-poor soils. It is the world's eleventh deepest lake at 505 m with a mean depth of 313 m. Its volume is 156 km3, with a hydraulic residence time of about 650-700 years, and is ice-free.

Lake Tahoe was once classified as ultra-oligotrophic (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 level of fertility has been moving away from this extraordinary condition. Extensive research on the spatial distribution of phytoplankton algae indicates a marked correspondence between growth rate and urbanization. Attached algae also demonstrate this pattern.

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. We now know that once nutrients enter the lake they remain in the water and recycled. Research has also shown a shift from frequent stimulation of algal growth by nitrogen to primarily phosphorus stimulation. Excessive atmospheric deposition of atmospheric nitrogen is considered responsible for this shift in nutrient stimulation. Since phosphorus is typically transported along with sediment, our findings underscore the importance of sediment control, erosion mitigation, acquisition of sensitive lands, and other means of restoration.

The State of Air Quality and Modeling, and Its Role in Ecosystem Management

The proximity of Lake Tahoe to upwind urban areas (San Francisco Bay Area and Sacramento Valley) and the widespread availability of local recreational opportunities, provide sources of air pollution to the Basin. In simplistic terms, the Lake Tahoe air basin can be defined by three major meteorological regimes, (1) summer day-time westerly winds, (2) summer night-time inversion, and (3) a persistent winter-time stagnant inversion. These meteorological regimes transport and trap pollutants near the lake surface, increasing the opportunity for these materials to deposit onto the lake surface. Due to the uniqueness of the Lake Tahoe basin, an air quality model specific to this region was to aid in management decisions with respect to air quality and ecosystem health.

The Lake Tahoe Airshed Model (LTAM) is designed to provide predictive capabilities for management. It also allows us to gather the disparate sources of air quality data at Lake Tahoe into a consistent framework. Pollution sources including automobiles and forest fires (both wildfires and prescribed fires) are input into the model; transport and a factor for deposition across the basin are predicted.

LTAM was used to evaluated prescribed during October, on 40-year (50 ha) and 20-year (100 ha) return cycles, as well as an August wildfire that would burn approximately 75% of the forested part of the Ward Creek watershed (1,500 ha). From the calculated emission parameters for the wildfire and prescribed fire scenarios, LTAM calculates the falloff in smoke $PM_{2.5}$ across the basin. Contrasted with the historical wildfire comparison, LTAM predicts massive violations of Federal and State $PM_{2.5}$ standards for the 20-year return. The historical wildfire is based on a burn scenario of 12 ha burned per day in 3 small (4 ha) wildfires. The 40-year return scenario predicts localized violations for the October period. A model run for the same scenario for a typical summer period predicts lesser violation, mostly due to the increased ventilation of the basin during that period. The hypothetical wildfire during August (1,500 ha) is predicted to completely fill the basin and beyond with smoke. Although the wildfire burns an order of magnitude more land than the prescribed fires, the number of resultant violation days is predicted by LTAM to be roughly equivalent. Further study of the impact of fire on the Lake Tahoe ecosystem, especially the impact of smoke on lake clarity, visibility, and human health, is necessary to better define parameters for integrated management models in general, and the LTAM in particular.

Lake Tahoe Nutrient Budgets

For decades, planning, regulatory and implementation actions in the Tahoe basin have focused on controlling nutrient and sediment inputs to the lake. Examples include, but are not limited to, acquisition of environmentally sensitive lands, building restrictions, BMP retrofitting, erosion control, installation of BMPs for treatment of surface runoff, permits and education. Now that the public and private sectors are working in cooperation to achieve environmental restoration, it is more important than ever that there are budgets which quantify the critical sources of nutrients and sediment. Prioritization of restoration projects depends on identifying the critical sources of these materials.

Five major categories of nutrient loading to Lake Tahoe have been identified (1) direct atmospheric deposition and precipitation, (2) stream discharge, (3) overland runoff directly to lake, (4) groundwater and (5) shoreline erosion. The major losses include settling of material from the water column to the bottom and discharge to the Truckee River, the sole tributary outflow. We provide preliminary estimates for phosphorus (P) and nitrogen (N) expressed as metric tons per year.

Total 418.1 45.7

The budget clearly suggests the importance of direct runoff as an important P source from urban areas and highlights the need for additional study in this area. At the same time, the contribution of atmospheric deposition to the N budget clearly dominates other sources. Heyvaert (unpub. data) has found that nutrient sedimentation losses to the bottom of Lake Tahoe are 401.7 MT for total-N and 52.8 MT for total P. These agree remarkably well with the independent loading estimates given above. This close agreement give us increased confidence that the loading rates are representative.

Paleolimnological Reconstruction of Baseline Conditions and Ecosystem Response to Anthropogenic Disturbance

Lake sediments accumulate material derived from the watershed and from the overlying water column and, over time a physical record accrues. Biogeochemical analysis of this record can provide useful information about lake response to changing conditions, whether from natural causes or from anthropogenic disturbance in the watershed. The analysis of lake sediment cores allows us to examine ecosystem processes at a longer and more relevant time scale than is usually attained from available monitoring data. When used in conjunction with process-oriented research that includes both modeling and the analysis of long-term data, this approach can also significantly improve our efforts to forecast ecosystem response to contemporary watershed disturbance. Over the years several sediment cores have been extracted from various points within the lake to determine spatial and long-term patterns of sediment composition and accumulation.

In the Tahoe basin there have been two major episodes of watershed disturbance since it was first described by European-Americans in 1844. The first event was extensive clear-cut logging associated with the Comstock era that began in the 1860s and continued into the 1890s. The second began with rapid urbanization in the late 1950s and continues to this day. In excess of 50,000 people permanently reside in the Tahoe basin. Four times that many can be in the Basin on any given day during the tourist seasons .

We now have a relatively reliable geochronology for the Tahoe sediments, constructed from ^{210}Pb and ^{14}C data. These data indicate significant basin-wide changes 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—1900. That period was followed by a 3—5 fold decrease in mass sedimentation rates during the early twentieth century. These lower sedimentation rates then persisted until urbanization began in the Tahoe basin after World War II. Pre-disturbance sedimentation rates were estimated from ^{14}C. The long-term average rate was 0.006 (± 0.002) g cm^{-2} y^{-1}, which is just slightly less than the sedimentation rate that was estimated for the period intervening between Comstock logging and urbanization. Since these rates are comparable, it would suggest that landscape recovery was rapid after clear-cut logging ended and that lake sedimentation rates dropped almost back to pre-disturbance levels.

Forest Health in the Tahoe Basin

As in many areas of the western U.S., periodic fire in the coniferous forests of the

Tahoe basin is considered to be a defining influence on ecosystem function and "health", altering fundamental plant, soil and microclimate conditions. Historically, frequent low-intensity fire has been the main disturbance dynamic driving ecosystem structure, function and composition. Within the last century, however, fire suppression and logging (both clear-cutting and selective harvests) have significantly altered stand conditions by increasing stem densities of shade-tolerant species, soil litter depth and understory shading. Both understory and overstory tree densities have increased dramatically throughout basin forests; in particular, there has been a doubling in the importance of white fir and incense cedar and a decline in the importance of Jeffrey pine and sugar pine by 50%. Sites that have been previously logged currently exhibit the highest stem densities for both overstory and understory trees. In association with a recent drought, highly visible levels of tree mortality in the Tahoe basin began in the mid-1980s. Based on 1997 and 1998 ground surveys of 31 stands in the basin, overall cumulative tree mortality in the lower montane forests ranges from 9% to 33% in 31 sampled stands with mean mortality of 25% for previously logged stands (i.e. seral stands) and 21% for old growth stands that have never been logged.

In many stands, these conditions are outside the forest's historic range of variability, fundamentally altering ecosystem processes. It has become apparent that in fire-dependent ecosystems, the absence of fire will lead to pests (often in conjunction with drought. Epidemic levels of bark beetles are clearly the most important cause of tree death in the past ten years in the Tahoe basin. A number of reports show increased mortality of Jeffrey pine due to the Jeffrey Pine beetle (*Dendroctonus jeffreyi*) and white fir due to the fir engraver beetle (*Scolytus ventralis*) during the drought years of 1987-1993.

The condition of Lake Tahoe forests has become an important concern for residents and forest managers of the basin. In light of the current state of Lake Tahoe forests, how should these lands be managed? The most critical need for Lake Tahoe forests is to set the goals that will be used to determine the direction of forest management. Science cannot not set societal goals; the major role scientists will play is to offer a series of alternative management schemes and potential outcomes from an initial set of objectives. In California, Lake Tahoe forests, along with the National Parks, are somewhat unique in that there is little pressure for a sustained timber harvest to maintain traditional logging communities. In an urbanized environment dependent on tourism, prevention of catastrophic fire and aesthetics are likely be the main concerns. However, goals such as prevention of catastrophic fire to protect property may not necessarily be compatible with goals that call for old growth restoration. The ability to partition the needs of an urbanized population from needs of natural ecosystem functioning will require much discussion among interested parties. If true ecosystem-based management is to take place in Lake Tahoe forests, managers must design any forest treatment with the collection of scientific data in mind. Otherwise, the ability of managers in the future to adapt to changing conditions will be compromised.

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AIR QUALITY AND MODELING AND ITS ROLE IN ECOSYSTEM MANAGEMENT AT LAKE TAHOE

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Lake Tahoe is a large fresh water lake at an elevation of 1,898 meters on the border between the states of California and Nevada in North America. This unique ecosystem is marked by a cold deep lake surrounded by an air basin defined by high mountains with a dramatic vertical relief. The presence of the cold lake at the bottom of this basin defines an atmospheric regime that, in the absence of strong synoptic weather systems, develops very strong (to 10° C), shallow (30 m) subsidence and radiation inversions at all times throughout the year. In addition, the rapid radiation cooling at night generates gentle (1 meter/second) but predictable down slope winds each night, moving from the ridge tops down over the developed areas at the edge of the lake and out over the lake itself. Local pollutant sources within this bowl are trapped by inversions, greatly limiting the volume of air into which they can be mixed, which then allows them to build-up to elevated concentrations. Further, the down slope winds each night move local pollutants from developed areas around the periphery of the lake out over the lake, increasing the opportunity for these pollutants to deposit into the lake itself. This meteorological regime, weak or calm winds and a strong inversion, is the most common pattern at all times of the year (Cahill et al, 1997).

The location of Lake Tahoe directly to the east of the crest of the Sierra Nevada creates the second most common meteorological regime, that of transport from the Sacramento Valley into the Lake Tahoe basin by mountain upslope winds. This patterns develops when the western slopes of the Sierra Nevada are heated, causing the air to rise in a chimney effect and move upslope to the Sierra crest and over into the basin. The strength of this pattern depends on the amount of heating, and thus is strongest in summer, beginning in April and essentially ceasing in late October (Cahill et al, 1997). This upslope transport pattern is strengthened and made even more frequent by the alignment of the Sierra Nevada range across the prevailing westerlies common at this latitude, which combine with the terrain winds to force air up and over the Sierra Nevada from upwind sources in the Sacramento Valley.

The close proximity of the basin to upwind urban areas and the widespread availability of recreational opportunities both provide a source of transported air pollution and bring a high concentration of visitors to the basin. Due to the topography and location, simplification of the Lake Tahoe air basin is defined by three major meteorological regimes, the summer daytime westerly winds, the summer nighttime inversion and a persistent wintertime stagnant inversion. These meteorological regimes transport and then trap pollutants near the lake surface. Recently, measurements of Lake Tahoe indicate a loss of lake clarity which is significantly coupled to an atmospheric source of both nutrients (Jassby et al., 1994) and fine particles (Cliff and Cahill, 2000). Due to the uniqueness of the Lake Tahoe basin, an air quality model specific to this region was developed as part of the Lake Tahoe Watershed Assessment program to aid in management decisions with respect to air quality and ecosystem health.

The Lake Tahoe Airshed Model (LTAM) is a heuristic eulerian model designed to provide predictive capabilities for management of the basin. Pollution sources including automobiles and forest fires (both wildfires and prescribed fires) are input into the model, and transport and a factor for deposition across the basin are predicted. The LTAM is an array of 1248-2.56 km^2 (1 mi^2) cells across the basin encoded on a Microsoft Excel spread sheet. The domain is 72 km (45 miles) north to south (Truckee to Echo Summit) and 42 km (26 miles) west to east (Ward Peak to Spooner Summit). All but the most southern end of the watershed is taken into account by the model. The LTAM is semi-empirical in design, and incorporates all available air quality measurements at Lake Tahoe, 1967-present, plus aspects of meteorological and aerometric theory. Free variables (traffic flow, acres burned in the forest, population density, etc.) are assumed to be linear with pollutant emissions. This model is a heuristic tool used to gather the disparate sources of air quality data at Lake Tahoe into a consistent framework.

The USFS Lake Tahoe Air-shed Model (LTAM) is the component of the overall Lake Tahoe basin Watershed models designed to provide information of the role of the atmosphere in the health and welfare concerns of the Lake Tahoe basin. It has as its two major immediate goals: 1) To predict the concentration of pollutants in the Lake Tahoe basin at spatially diverse locations where no data exist. 2) To predict the potential for atmospheric deposition of nutrients and fine particles to the watershed and lake by determining spatial concentration of pollutants within the basin. A thorough description of the LTAM, inputs to the model and several output scenarios is given in Cliff and Cahill, 2000 (Watershed Assessment).

Scenarios for the Watershed Assessment modeling integration were developed to present the type of modeling results that are possible with single medium (in this case air quality) models designed specifically for the Lake Tahoe basin. The scenarios evaluated prescribed burns in the Ward Creek watershed on 40- and 20-year cycles occurring in October, and a wildfire that would burn approximately 75% of the forested part of the Ward Creek watershed in August. From the calculated emission parameters for the wildfire and prescribed fire scenarios, the LTAM calculates the falloff in smoke $PM_{2.5}$ across the basin. The resultant values from the LTAM are graphed as a concentration versus location and then plotted over a map of the area represented by the model. A comparison of the three scenarios (excluding the large wildfire) is shown in Figure 1. Contrasted with the historical wildfire comparison (Figure 1a), it is seen that the

LTAM predicts massive violations of Federal and State $PM_{2.5}$ standards for the 20-year return scenario (Figure 1c). The historical wildfire is an analysis of past conditions based on a 40-year return in the basin divided among the total burn season, equaling about 30 acres burned per day in 3 small (10 acre) wildfires (Figure 1a). The 40-year return scenario predicts localized violations for the October period (Figure 1b). A model run for the same scenario for a typical summer period (not shown) predicts lesser violation, mostly due to the increased ventilation of the basin during that period. The hypothetical wildfire during August, burning over 3700 acres, is predicted to completely fill the basin and beyond with smoke (Cliff and Cahill, 2000). Although the wildfire burns an order of magnitude more land than the prescribed fires, the number of resultant violation days is predicted by the LTAM to be roughly equivalent. That is about 2 to 3 violation days for the 40-year fire, 3 days for the 20-year fire, and 4 to 5 days for the wildfire. The apparent discrepancy of this fact is due mostly to the increased ventilation of the basin during the late spring and summer months. Furthermore, increased lofting of smoke in a wildfire results in impact at greater downwind distance than in a prescribed fire situation. It should be noted that the LTAM is capable of only limited predictions at this time. Further study of the impact of fire on the Lake Tahoe ecosystem, especially the impact of smoke on lake clarity, visibility, and human health, is necessary to better define parameters for integrated management models in general, and the LTAM in particular.

Air quality modeling in the Lake Tahoe basin, although at the nadir of development, is capable of aiding in ecosystem health management. The Lake Tahoe Air-shed Model (LTAM) is designed for use as a heuristic tool to gather disparate sources of air quality data at Lake Tahoe into a consistent framework. The most significant finding from the construction and use of the LTAM is that pollutants are most likely to deposit to the lake surface and hence potentially degrade lake clarity at times of intense inversion. Atmospheric inversion at Lake Tahoe is the most predominant meteorological condition during the evenings during the summer months, and all day throughout the inter-storm winter period. An evaluation of $PM_{2.5}$ for hypothetical wildfire and prescribed fires in the Ward Creek Watershed has been performed. The result of this evaluation indicates that, for the prescribed fires, a fall burn is particularly troublesome from the standpoint of air quality. The atmospheric inversions that tend to be present during the fall inhibits ventilation of the Lake Tahoe basin and hence allows buildup of the concentration of $PM_{2.5}$. Currently, not enough is known about the chemical composition and speciation of prescribed fire smoke to evaluate the impact of these prescribed fires on the clarity of Lake Tahoe. It is known, however, that $PM_{2.5}$ is a pollutant from the perspective of human health. The potential for violations of federal, state and basin air quality standards (Molenar et al., 1994) based on visibility is also expected from prescribed fire. In general, to better evaluate the impact of air quality and ecosystem health at Lake Tahoe requires further study. It is imperative to understand the link between emission, transport and deposition of air constituents throughout the basin to better constrain integrated modeling tools for management use.

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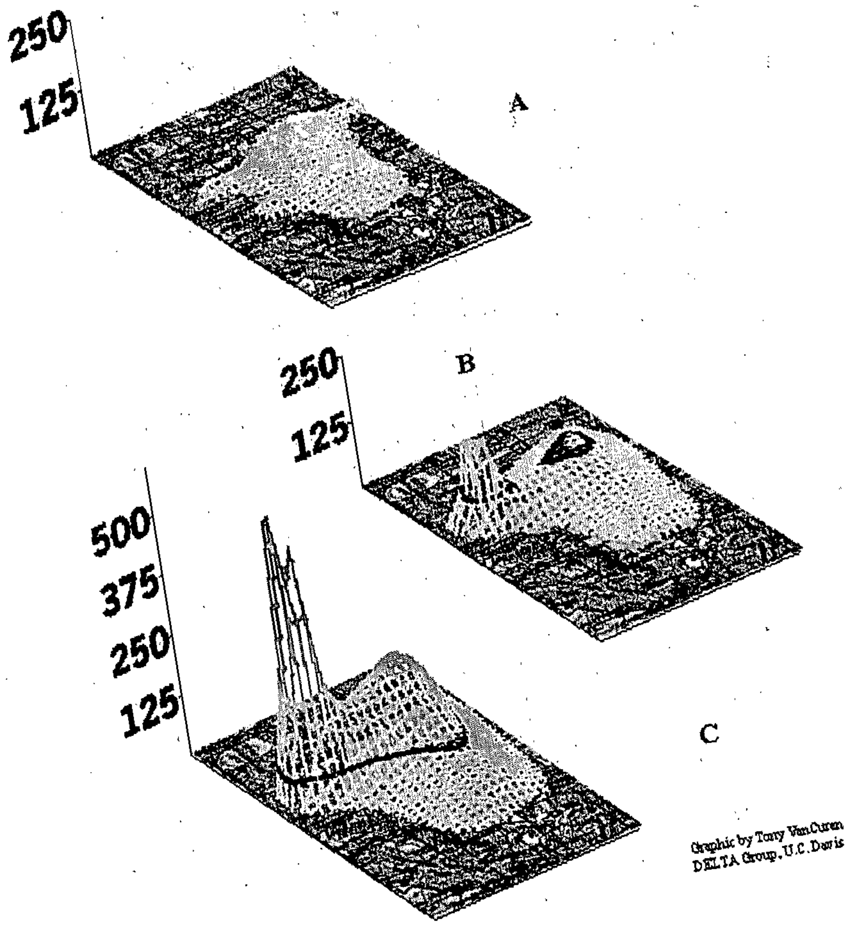
Molenar, John V., D. Dietrich and D. Cismoski, T. Cahill, and P. Wakabayashi. Aerosols and visibility at Lake Tahoe. Air and Waste Management Society, Fine Particles and Visibility Conference (1994).

Figure 1. $PM_{2.5}$ concentration predictions from LTAM based on a 24-hour average superimposed on the basin map. Comparison of 3 fire scenarios in the Lake Tahoe basin. Figure **A** is the historical wildfire (30-40 acres). Figures **B** and **C** are hypothetical prescribed fire scenarios located in the Ward Creek Watershed. Figure **B** is a 124 acre prescribed fire, and **C** is a 248 acre prescribed fire representing a 40 and 20 year total fire return time to the basin, respectively. The black isoplith is set at 65 $\mu g/m^3$, which is the (proposed) Federal 24-hour standard for $PM_{2.5}$. The peak concentration for **A**, **B**, and **C** are 29, 165, and 500 $\mu g/m^3$, respectively.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Graphic by Tony VanCuren
DELTA Group, U.C. Davis

Characterization of Nitrogen in Atmospheric Fine Particles from Outside of the Lake Tahoe Basin

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Introduction

As revealed by measurements of the Tahoe Research Group, direct atmospheric deposition provides over half of the nitrogen and approximately 20% of the phosphorous input to Lake Tahoe. Because these atmospheric nutrients play a critical role in the declining clarity of the lake, it is important to understand their origin. One of the outstanding issues related to this is determining the fraction of atmospheric deposition due to sources from within, and from outside of, the Lake Tahoe basin. The relative importance of in-basin versus out-of-basin sources has a direct bearing on the effectiveness of nutrient control strategies for the lake.

Given the prevailing westerly winds during the summer, likely sources of out-of-basin nutrients and contaminants to Lake Tahoe during this season include the Bay Area, Central Valley and foothills regions. The goal of this present work was to characterize the nitrogen concentrations in fine atmospheric particles in the Central Valley in order to begin to assess the potential of an out-of-basin source of nitrogen from this region. We focused on fine particles because they have a greater potential for long-range transport relative to larger particles. To carry out this work we collected biweekly samples of $PM_{2.5}$ (particles with diameters $\leq 2.5\ \mu m$) in Davis, California from August of 1997 to July of 1998. After collection, particles were extracted with water (to measure the water-soluble fraction) and analyzed for both inorganic and organic nitrogen species.

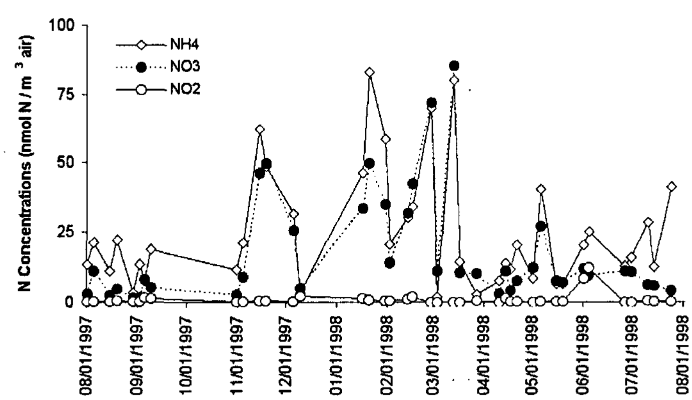
RESULTS

Inorganic Nitrogen (IN)

The concentration of particulate inorganic nitrogen ranged from 6 — 190 nmol N/m^3-air during the year of sampling and had a mean value of 44 nmol N/m^3-air.

The relative concentrations and temporal changes of the inorganic nitrogen species — ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-) — are shown in Figure 1. From this data it is clear that, on an N-atom basis, ammonium and nitrate are the dominant components of inorganic nitrogen in $PM_{2.5}$ while nitrite is generally negligible. As listed in Table 1, ammonium and nitrate on average accounted for 59 and 38%, respectively, of the inorganic nitrogen in $PM_{2.5}$. Figure 1 also reveals that the highest concentrations of particulate inorganic nitrogen in Davis occurred during the winter and early spring. However, because of meteorological conditions during the winter (e.g., a capping of the Tahoe air basin by wintertime inversions), it is unlikely that transport of $PM_{2.5}$ from the Central Valley to Lake Tahoe is significant during winter.

Figure 1. Concentrations of Inorganic Nitrogen in Fine Particles from Davis, CA



Organic Nitrogen (ON)

Most previous studies of atmospheric nitrogen deposition have considered only inorganic forms of N. However, several studies, including that of Jassby et al. for Lake Tahoe, have shown that organic species can represent a significant portion of the total nitrogen in atmospheric deposition. Because of this, we also measured organic nitrogen in the Davis $PM_{2.5}$ samples.

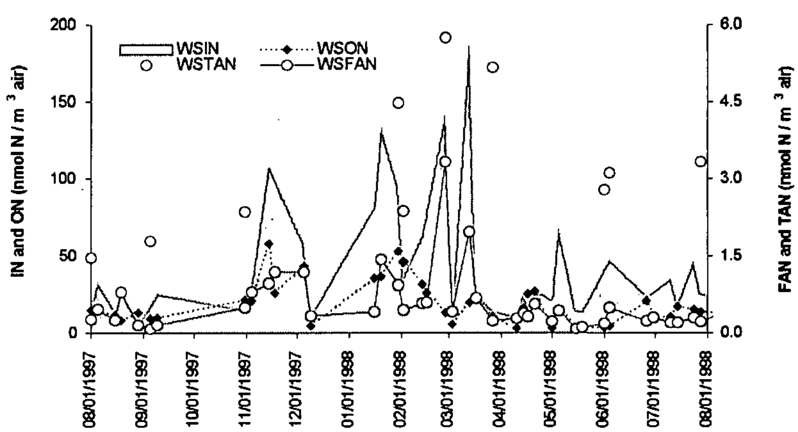
The concentration of particulate organic nitrogen in the samples ranged from 3 — 58 nmol N/m^3-air and had a mean value of 19 nmol N/m^3-air. As shown in Figure 2, levels of organic nitrogen were generally comparable to, but usually smaller than, concentrations of inorganic nitrogen in a given sample. In the 41 $PM_{2.5}$ samples analyzed, ON represented from 9 — 72% of the total nitrogen in the samples, with a mean value of 34%. Thus organic nitrogen was a significant portion of the total nitrogen in fine particles from Davis. A number of recent papers have shown that roughly half or more of ON is readily utilizable by aquatic bacteria and phytoplankton, indicating that the water-soluble organic nitrogen in Davis $PM_{2.5}$ could also be an important source of nutrient nitrogen to Lake Tahoe and other aquatic ecosystems.

Table 1. Contributions of Individual Nitrogen Species (or Class) to Specified Nitrogen Pools in $PM_{2.5}$ from Davis, California (mol N / mol N, expressed as %).

	Min	Max	Median	Mean	Std. Dev.
NH_4^+ / IN	15	90	59	59	17
NO_3^- / IN	10	85	40	38	16
ON / TN	9	72	33	34	15
FAN / ON	0.8	24	2	4	4
TAN / ON	8	71	23	33	24

Abbreviations: IN = inorganic nitrogen; ON = organic nitrogen; TN = total nitrogen (i.e., ON + IN); FAN = free amino nitrogen; TAN = total amino nitrogen.

Figure 2: Concentrations of Organic Nitrogen in Fine Particles from Davis, CA



We also determined the concentration of free and combined (e.g., proteins and peptides) amino compounds in the $PM_{2.5}$ samples. Based on previously published reports, amino acids are apparently ubiquitous in atmospheric deposition. However, no previous studies have determined what fraction of the total organic nitrogen is accounted for by amino compounds. Table 1 and Figure 2 show that while dissolved, free amino compounds represent only a small portion of ON (mean value of 4%), combined amino compounds are much more significant. As shown in Table 1, combined amines accounted for 8 — 71% of ON (mean value = 33%), indicating that proteins, peptides, and other combined amines are a significant portion of organic nitrogen.

DISCUSSION AND FUTURE WORK

Our results show that there are significant concentrations of particulate nitrogen in the Central Valley throughout the year. This preliminary result suggests that the Central Valley might be a significant out-of-basin source of nitrogen to Lake Tahoe. The ratio of organic to total nitrogen in our Davis $PM_{2.5}$ samples is in the same range as values reported for wet and dry deposition to Lake Tahoe by Jassby and co-workers. Although this is a very non-specific indicator, it is not inconsistent with the possibility that the Central Valley is a source of nutrients to the Tahoe basin.

In conjunction with Professor John Carroll, we plan to test the significance of this potential out-of-basin source by carrying out aircraft sampling along a transect from the Central Valley to Lake Tahoe. During this sampling we will be collecting both gaseous and particulate nitrogen to give a complete picture of the atmospheric nitrogen reservoir and how it varies along the transect. In addition, we will also attempt to measure phosphorous during this sampling in order to get a fuller sense of the importance of out-of-basin nutrient sources.

Monitoring Lake Tahoe Hydrodynamics

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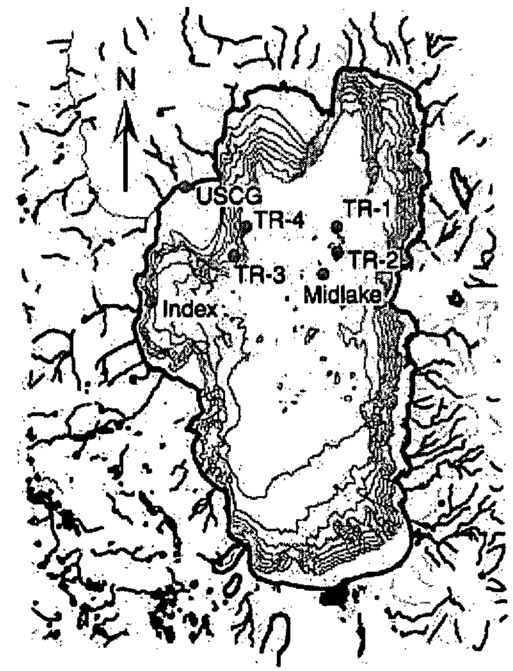
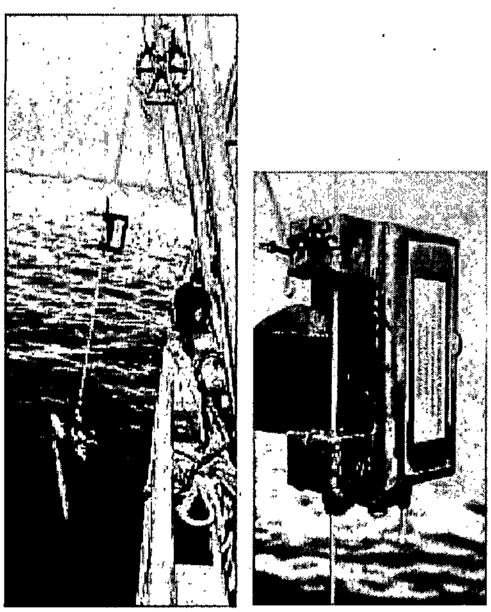
A thermistor chain has been deployed during winter months at the Midlake station of Lake Tahoe (see map to the right) since 1995. A second chain, located at the western shore (Index station), was added in 1997. These chains have since then been operated during the winter months but they were deployed for the first time during summer, in 1999. Each chain consists of several self-contained high accuracy thermistors that have an accuracy of better than 0.005 °C and record temperature every 2 minutes (see picture below). The temperature data provide information on the lake's density stratification as well as internal wave climate, both of which are of fundamental importance for understanding the hydrodynamics of the lake. At the end of 1998, and in 1999, water velocity measurements were performed near the Index station with acoustic Doppler current meters (see picture next page).



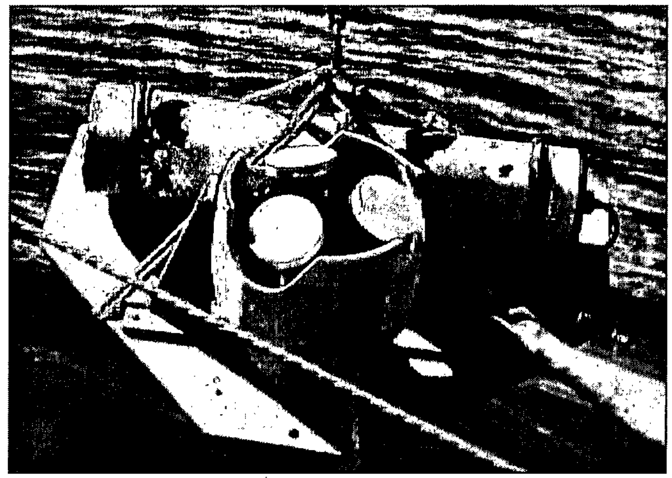
Map of Lake Tahoe and the monitoring stations.

A meteorological station has been operated by the UCD at the U.S. Coast Guard (USCG) pier by Tahoe City (see picture next page). The station has provided valuable weather data right at lake's surface. The data are used for the interpretation of the measured water parameters as well as an input for hydrodynamic models. There are great spatial differences in meteorology across a large lake like Lake Tahoe. The wind is in particular non-uniform over the lake's surface. It is a very important input for any modeling effort in the lake. Additional wind stations are proposed around the lake, as well as on the lake, potentially on the rafts that are currently operated by NASA.



Self-contained thermistors on a thermistor chain.

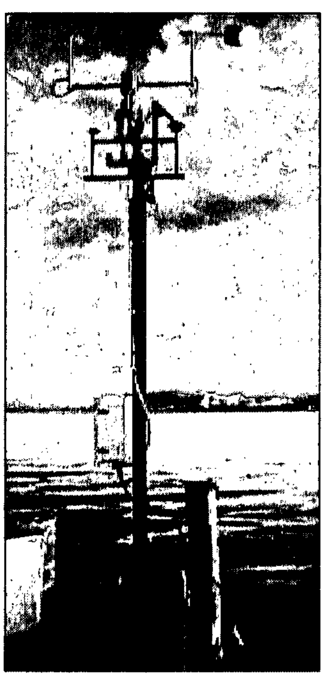
Typically, thermal stratification intensifies from February to April and reaches maximum in August, at which time the thermocline is located at approximately 20 to 30 m depth. Slow weakening of the stratification leads to approximately isothermal conditions in mid-winter. Complete mixing of the water column is dependent on the meteorological forcing and does not occur every year. This variability in complete mixing of the lake has been verified with the present hydrodynamic studies. The studies have revealed a complex pattern in the vertical and horizontal mixing patterns of the lake, and suggested that complete winter mixing of the water column at the Midlake station is strongly dependent on horizontal flow of colder water from the near shore areas.



Acoustic Doppler Profiler (ADP)

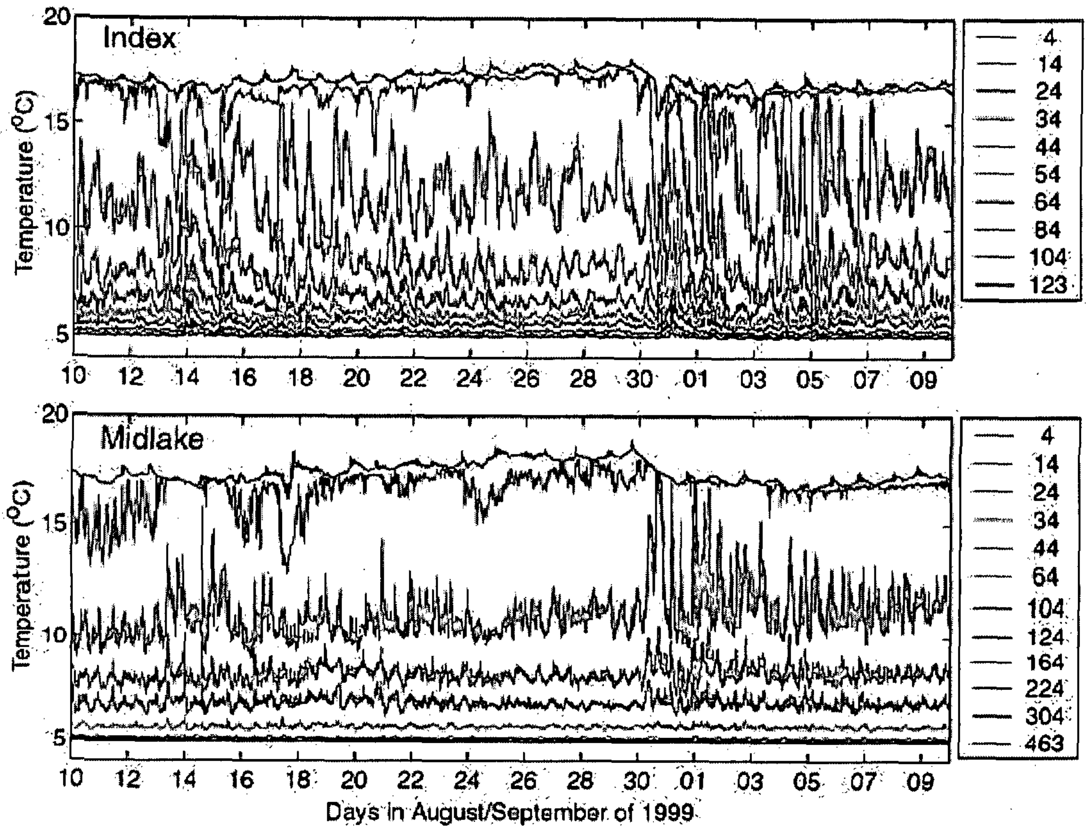
The thermistor data collected during the summer of 1999 (see next page), shows how strongly stratified the lake is in summer. Temperatures at and below 104 m depth were approximately 5 °C, whereas at the lake's surface they were as high as approximately 18 °C. The water column can in general be separated into three layers: top, intermediate and bottom. The water column does not have a sharp thermocline. Instead, the largest temperature difference occurs over the intermediate layer. This layer ranges from approximately 15 to 50 m depth, and experiences high internal wave activity.

The plot following the thermistor plot shows the velocity measured at the Index station during the same period, as well as the acoustic signal strength recorded by the instrument at any given time. These data were collected with Sontek Argonauts (picture not shown), which are acoustic Doppler current meters that provide the average velocity in a one-meter high cell. The acoustic signal strength of the instrument is a measure of the concentration of suspended particles in the water, since the instrument estimates the water velocity from the reflected signal of suspended particles (e.g. sediment and biological matter). The units of the signal, counts, are given on a logarithmic scale (1 count = 0.43 dB), so we can see from the graph that the concentration of suspended particles varies dramatically. One Argonaut was located in the surface (or top) layer (at 7 m depth), and the other was located relatively low in the strongly stratified intermediate layer (at 49 m depth). We can see the large surface current, as high as approximately 20 cm/s, during a strong wind event on August 30. This event resulted in some mixing between the surface and intermediate layers, as can be seen from the decrease in surface temperatures on and after August 30. The acoustic signal strength from the Argonauts becomes similar for the two instruments after this event, further supporting the mixing.

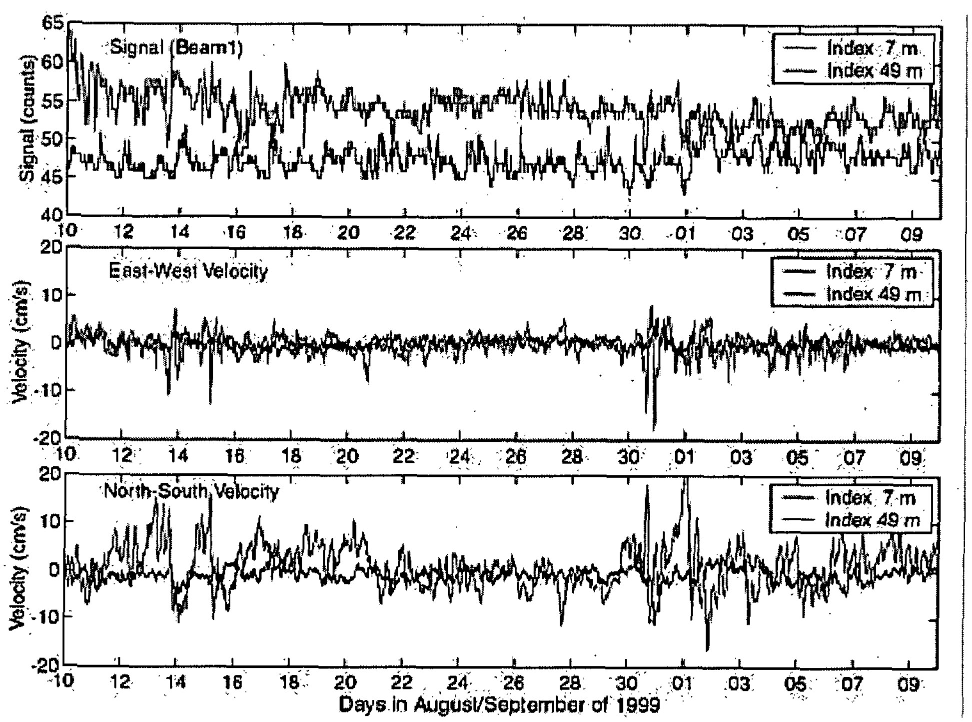


Weather station at the USCG pier.

The intense internal wave activity observed in the collected data has raised concerns about the contribution of the shearing and breaking of these internal waves on the lateral boundaries of the lake, to the lake water clarity. The thermistor chain data from the winter studies have also indicated a highly energetic internal wave field in Lake Tahoe during the winter months. The internal waves have the potential to resuspend sediments off the sloping near shore bottom. Lake water clarity can be influenced directly by the presence of the particles in the water column, as well as indirectly by releasing



Thermistor data collected in summer of 1999 at the Index and Midlake stations.

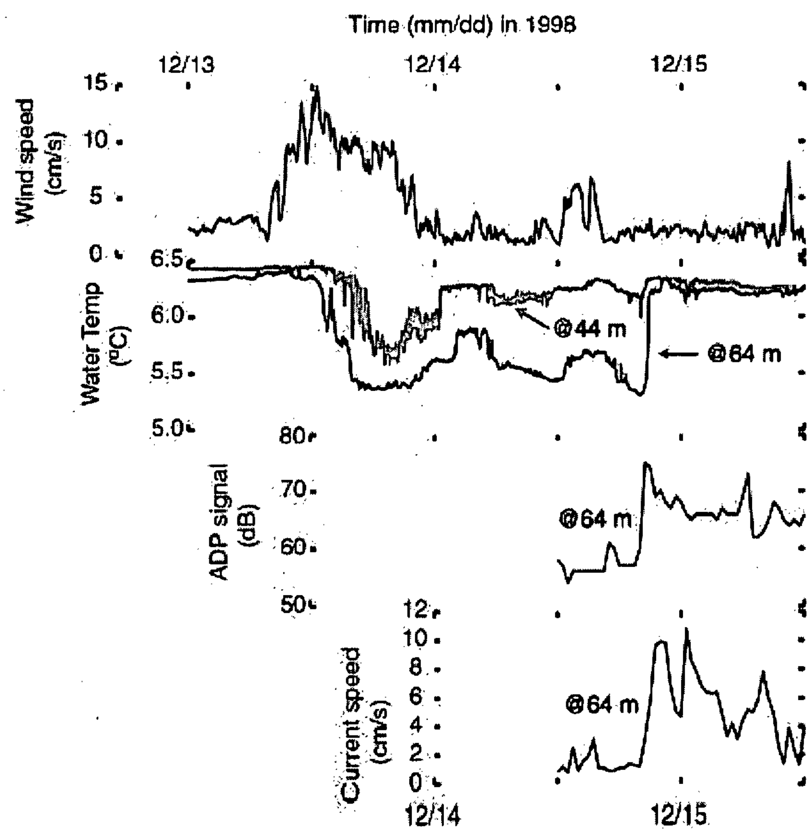


Acoustic signal strength and horizontal velocity collected at the Index station with Argonauts.

nutrients that become available to phytoplankton.

Observed data collected with an acoustic Doppler profiler (ADP) indicated intense mixing due to internal wave activity, during a meteorological event in December of 1998 on the steep slope near the Index station on the western shore (see map). On Decemer 13, a strong wind resulted in upwelling of the water column at the western shore. The upwelling brought colder bottom water higher in the water column, which explains the colder temperatures read by the thermistors at 44 and 64 m depths (see figure below). The strong wind lasted more than half a day. Once it ceased, the upwelling of the water was relaxed to a great extent. The 64 m logger showed some temperature oscillations, until finally it was recording the same temperatures as the 44 m logger. The surface water had been forced downwards (downwelling) and the thermistor at 64 m depth recorded a sudden increase in temperature (about 1°C change). At that time, the ADP showed a sudden increase in signal strength at that depth, a measure of increased concentration of particulate matter. Since the ADP was deployed in approximately 70 m of water, this high signal strength can be attributed to resuspension of sediments. The speed of the current increased from about 1 cm/s to 10 cm/s and the measured direction of the current became more uniform (see figure below).

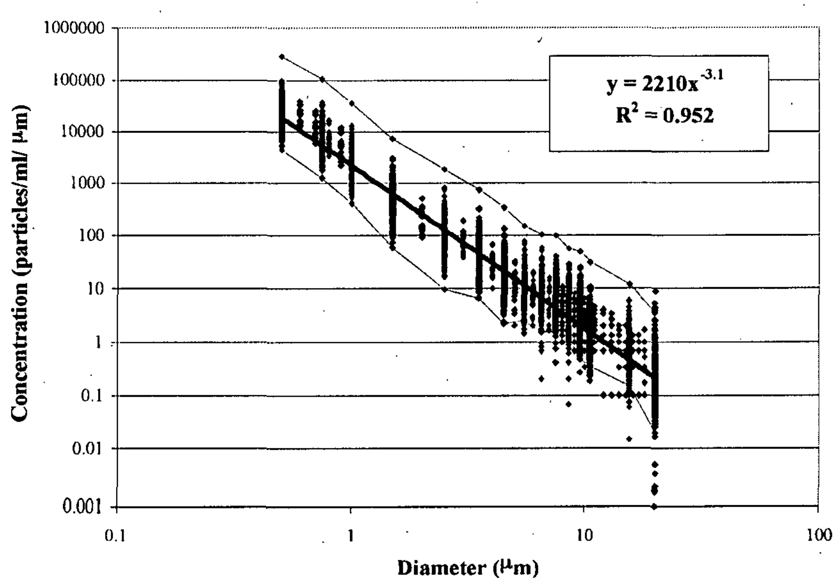
These mechanisms in Lake Tahoe are not yet well understood. They can potentially have significant effects on the lake water clarity as well on the ecosystem in general, since they can attribute to the nutrient availability. Their study is an integral part of Lake Tahoe's hydrodynamic monitoring effort.



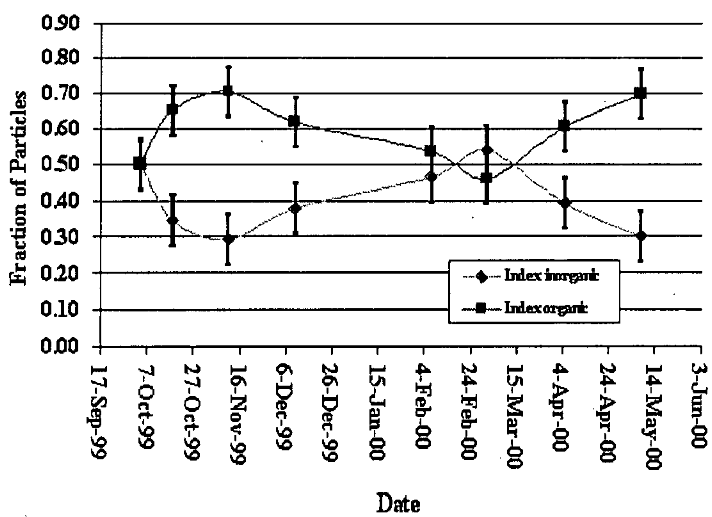
Wind speed, water temperature and ADP signal strength and current speed measured near the Index station in 70 m of water.

Lake Tahoe Particle Characterization 1999-2000

Jennifer Coker and Geoffrey Schladow Department of Civil & Environmental Engineering, University of California, Davis, CA 95616 Lake Tahoe particles were characterized in terms of number concentration, size distribution, and percentage of mineral and organic particles throughout 1999-2000. These results were used to estimate the magnitude of the scattering coefficient and to estimate the roles that individual types of particles had on the clarity of Lake Tahoe water. Particles were analyzed for number concentration and size distribution using an LS-200 (Liquid Sampler) and LiQuilaz-S05-HF sensor manufactured by Particle Measuring Systems Inc (Boulder, Colorado). The system measures particles with diameters between 0.5 μm and 20 μm in diameter, the size range that scatters the greatest amount of light. This size range is also of interest because particles with these small diameters have extremely slow settling velocities, and tend to be retained in the water column. The fraction of organic to inorganic particles was determined using Scanning Electron Microscopy coupled with X-ray energy spectroscopy. In Figure 1, results are shown for 409 particle size distributions measured for both the Index and Mid lake stations throughout 1999-2000. Normalized particle concentrations are presented (normalized by the width of the channel, i.e. the concentration of particles between diameters 1 μ m and 2 μ m would be divided by 1μ m, thus the units are particles/ml/μ m channel width). As is consistent with the literature, it Figure 1: Index and Mid lake station Particle Size Distributions 1999-2000



was found that the number of particles increased rapidly with decreasing size, and the majority of particles were smaller than 2 μ m in diameter. All particle size distributions were described by a one-parameter hyperbolic distribution with exponents between —2.5 to —3.5, most having r^2 values of greater than 0.97. As can be seen in Figure 1, the best-fit trendline has an exponent of —3.1, and the r^2 value of 0.95. The highest particle number concentration for the Mid lake station, 130,000 particles/ml, was measured on 9/13/99 at a depth of 230 m. This concentration was confined to thin layer of water, at most stretching from just below 220 m to just above 240 m. Assuming this sample was not contaminated in some fashion, the average depth weighted particle concentration for the Mid lake station is approximately 11,900 particles/ml. However, if we assume that this sample was contaminated, the maximum particle concentration would be 45,000 particles/ml, and the average depth weighted concentration would be closer to 11,600 particles/ml. The minimum concentration measured at the Mid lake station was 1700 particles/ml. The maximum and minimum concentrations measured at the Index station were 25,000 particles/ml and 1,800 particles/ml respectively. The average depth weighted particle concentration at the Index station was 7,600 particles/ml. While both maximum and minimum particle concentrations were measured at the Mid lake station, on average, the Index station has lower particle concentrations.



In Figure 2 and Figure 3 results are presented for the fraction of organic and mineral particles determined from X-ray energy spectroscopy for the Index station and Mid lake station respectively. A seasonal pattern is evident from Figure 2. In early October, the Figure 2: Fraction of organic to inorganic particles, Index Station 1999-2000 error bars denote 95% confidence ratio of organic to inorganic particles is about the same. Starting at the end of October through mid December, the ratio shifts, and begins to favor more organic particles. According to Jassby *et al.* (1999) thermal stratification usually peaks in August, and the thermocline begins to deepen in September. As the mixed layers reaches the 60 — 120 m region around December, it encounters the deep chlorophyll maximum, a common feature of Lake Tahoe and other deep water bodies. It appears that the subsequent upwelling of phytoplankton from this maximum, was the cause of the phytoplankton (organic particle) increase in the surface waters. From early February through early March, the ratio of particles again becomes approximately equal — either due to further deepening of the mixed layer into chlorophyll-depleted water from the hypolimnion which now dilutes the surface water and/or the beginning of the snowmelt. The last measurement, taken in early April shows the ratio has again shifted to be dominated by organic particles — perhaps due to warmer temperatures and increased availability of nutrients. There was considerably more variation in the ratio of organic to inorganic particles observed at the Mid lake station for 1999-2000. This variation in ratios is probably due to nutrient limitations found at the Mid lake station.

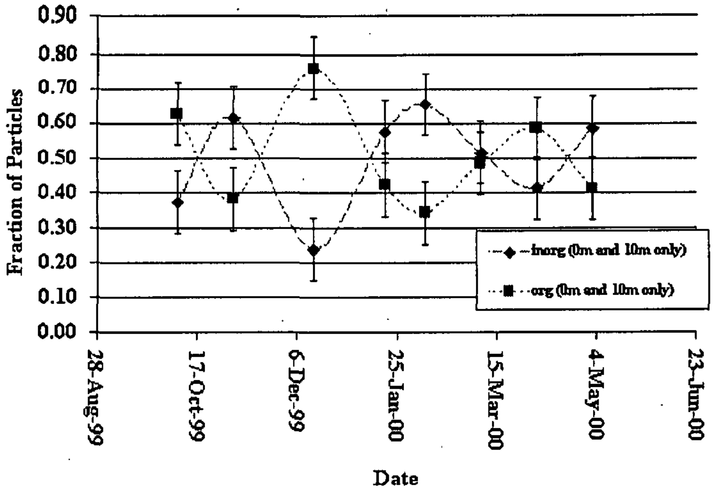


Figure 3: Fraction of organic to inorganic particles Mid lake station, error bars denote 95% confidence. In Figure 4 the cumulative contribution to the scattering coefficient is plotted versus particle diameter for a typical size distribution and number concentration of particles found in Lake Tahoe Surface water. Two extreme cases are considered —

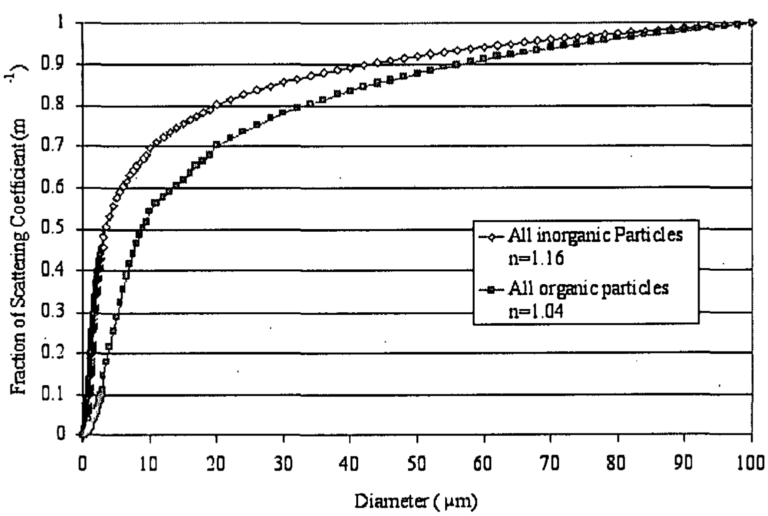


Figure 4: Fraction of Scattering at 550 nm vs particle size for a typical size distribution of Lake Tahoe surface water, exp=-3.14, C=4500 (Concentration of particles >0.5 um =9500 particles/ml) all inorganic particles and all organic particles. It is evident from Figure 4 that particles smaller than 10 μ m comprise the vast majority of particulate scattering (up to 70% for inorganic particles. Particles of diameters smaller than 3 μ m contribute 10% and 45% of the total scattering coefficient for organic particles and inorganic particles respectively. Comparison of estimates of absorption and scattering measured within days of each other have revealed that scattering is typically smaller than measured absorption, though it can range from 30%-200% of the absorption coefficient (Swift, personal communication). Although results are still somewhat preliminary, it appears that absorption may

dominate the beam attenuation coefficient during the time of year which does not include the spring snowmelt; this is consistent with the previous findings of Jassby et al. (1999) . Data is currently being collected and analyzed for that important period when clarity is at a seasonal minimum. It is still unclear to what extent nutrients are associated with suspended particles — a line of research that will be undertaken.

Lake Tahoe Optical Model

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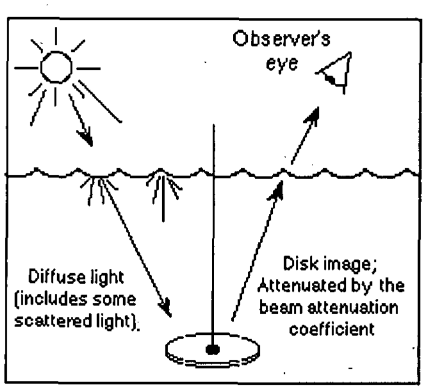
Introduction

One of the earliest signs of ecological change in Lake Tahoe, and one of the most highly valued measures of its aesthetics, is its world-famous clarity and color. In the early 1960s, a 20-cm (8-inch) diameter white Secchi disk could be discerned at a depth of 32 m (105 feet), on average. By the late 1990s the Secchi depth had reduced to approximately 20 m (65 feet). Secchi depth is among the target thresholds, along with nutrient and sediment loading, etc., driving the strategies for environmental restoration and management of the Tahoe basin. The optical model under development by the TRG is part of the effort to quantitatively couple the effects of nutrient and sediment transport processes to the present and future clarity of the lake. The model will provide a tool for evaluating management and restoration strategies in the watershed and studying ecological processes in the lake.

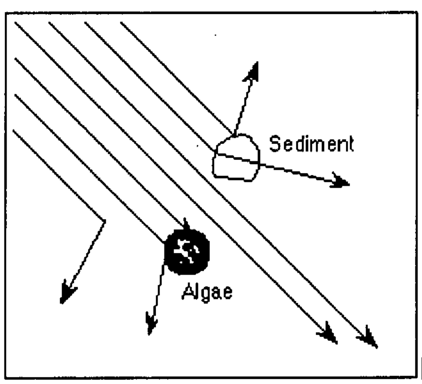
Secchi depth is a sensitive measure of light attenuation in clear water.

Secchi depth, and light absorption and scattering



As a beam of light travels, it is attenuated by scattering and absorption. Scattering and ab-sorption are called inherent optical properties (IOPs) because they do not depend on the amount or direction of sunlight. Suspended particles, dissolved material, and pure water itself contribute to attenuation. Pure water absorbs light in the red portion of the spectrum, and scatters very little light overall, causing very clear water to have a bright blue or azure appearance. Inorganic sediments strongly scatter light, and scatter more short wavelength (blue) light than long wavelength (red) light, lending sediment-laden water its reddish-brown color. Algal par-ticles scatter somewhat, but primarily are strong absorbers in the blue and red portions of the light spectrum. In a sense, their primary function is to absorb light and thereby convert it into chemical energy stored in organic matter. By absorbing red and blue light, the chlorophyll and related pigments in algae make the water appear green. Colored dissolved organic matter (CDOM) consists of humic substances and tannins from decayed plant matter, including algae and terrestrial plants. It strongly absorbs blue and ultraviolet light and in sufficiently high concentrations, looks like tea. All these sub-stances are present in Tahoe water. The chal-lenge has been to separate and quantify the contributions of these sub-stances to the loss of clarity.

A Secchi observation provides a sensitive and integrated measurement of attenuation. By understanding the scattering and absorbing characteristics of the dissolved and particulate matter in Tahoe, developing a mathematical model relating material concentration to clarity and Secchi depth, and verifying the model by comparing the predicted to the observed values, we can begin to develop a management tool.



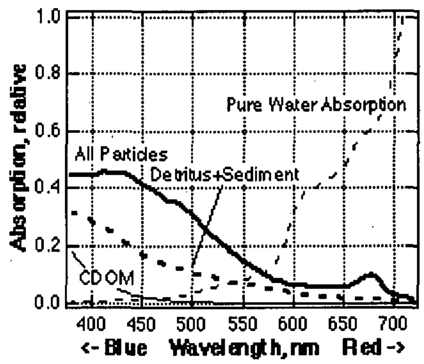
Light scattering and absorption by particles and water itself.

Optical Model Components

The formal relationship between the IOPs and Secchi depth are well developed (e.g., Tyler, 1968; Preisendorfer, 1986): The Secchi depth is the eye's contrast threshold (a quasi-constant) divided by the sum of the diffuse attenuation for down-welling light and the beam attenuation of light returning from the disk to the eye. These attenuations are functions of the absorption and scattering coefficients. The optical model takes CDOM and organic and inorganic particle concentrations, calculates the spectral scattering and absorption coefficients, weights these by the eye's photopic response, and uses Tyler's equation to arrive at a predicted Secchi depth.

Scattering

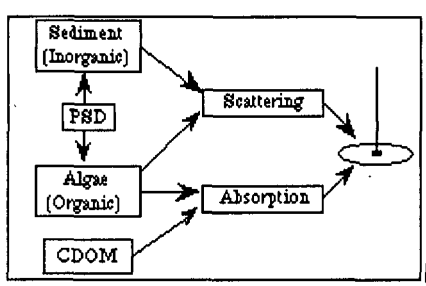
The wave nature of light causes it to scatter more strongly from very small particles of sizes on the order of a few wavelengths. The optical model takes the organic and inorganic particle size distributions (PSDs) into account in the scattering calculations. As is reported elsewhere in these summaries (Coker and Schladow), the typical PSDs in Tahoe water follows a hyperbolic distribution found in most natural systems, in which the number of particles is proportional to an inverse power of their diameter. A majority of the particles in the lake are 2 μm or less in diameter, in the size range that scatters light most strongly.



Materials in Tahoe water absorb light at distinctive wavelengths.

Absorption

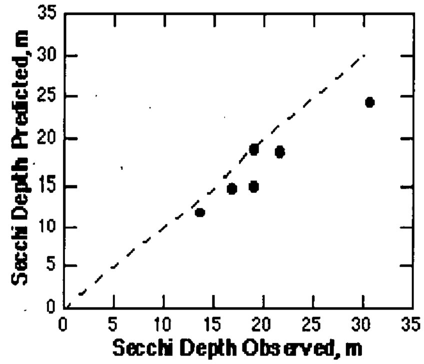
CDOM, though detectable in Tahoe water, contributes only ~4.5% of visible-light ab-sorption. This proportion drops to ~1.5% when weighted by the eye's photopic response to color. Attention has therefore focused on particulate material in the lake and tributary streams. We concentrate particles from measured volumes of lake water (often 1 to 2 liters) onto glass fiber filters and measure their spectral absorption in the laboratory. Particulate absorp-tion varies seasonally and with depth, but typ-ically about 55% of photopic absorption is due to soluble pigments; the remainder is due to other, insoluble organic and inorganic matter.



Principle parts of the Tahoe clarity model.

Findings and comparison between the model and observation

Field measurements and preliminary model calculations agree well over a wide range of Secchi depths (see below). Very fine particulates, both organic and inorganic, cause the reduced clarity of Lake Tahoe. Dissolved organic matter, while found in higher concentrations in streamwater, is not the cause of the seasonal or long-term loss of clarity. Inorganic (sediment) particles contribute disproportionately to clarity loss due to their higher scattering efficiency and slow settling rate. Continued study of the physical and biological processes affecting these particles is needed.



Comparison between observations and model.

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CHANGES IN MTBE AND BTEX CONCENTRATIONS IN LAKE TAHOE, CA-NV

FOLLOWING IMPLEMENTATION OF A BAN ON SELECTED

2-STROKE MARINE ENGINES

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INTRODUCTION

Discovery of the fuel oxygenate methyl tert-butyl ether (MTBE) in groundwater, lakes and reservoirs used for drinking water has raised considerable concern among health officials and water suppliers. The U.S. EPA has classified MTBE as a possible human carcinogen. Recent legislation in California has established primary and secondary drinking water standards at 13 $\mu g/L$ and 5 $\mu g/L$, respectively. Since 1997, the Lake Tahoe basin has received considerable state and national attention with regards to MTBE contamination of both groundwater drinking supplies and the lake itself.

Protection of the lake from controllable sources of pollution is required under its designation as an Outstanding National Water Resource (ONWR) as part of the federal Clean Water Act. Lake samples collected by the University of California, Davis - Tahoe Research Group (TRG), University of Nevada Reno (UNR), and the U.S. Geological Survey during the summers of 1997 and 1998 showed detectable levels of MTBE and the BTEX fuel constituents (benzene, toluene, ethylbenzene, and xylene), lake wide (e.g. Allen et al. 1998, Boughton and Lico 1998). Concentrations were shown to vary with the level of motorized watercraft traffic. However, at specific locations, levels exceeded not only the California drinking water standards but the higher U.S. EPA advisory value of 35 $\mu g/L$. Samples from the open water in the middle of the lake, where little summer boating occurs, revealed the presence of fuel constituents to a depth of 10 m, but at concentrations near or below the analytical levels of detection (mean value of 0.3 $\mu g/L$; Allen et al. 1998).

Along the shoreline of the lake where motorized watercraft activity is more common, fuel constituent concentrations were found to be about an order of magnitude higher (2.6 $\mu g/L$, mean value for MTBE). These shoreline concentrations were still below the established drinking water standards. In areas where motorized watercraft traffic is considered to be exceptionally high (marinas and fueling facilities), mean concentrations for both MTBE and benzene, during certain times of the summer boating season, exceeded primary drinking water standards. Further investigation by the California Air Resources Board (CARB) and UNR into the direct contribution of fuel constituents from various engine technologies revealed that the carbureted two stroke engines were contributing a disproportionate share of the fuel load to Lake Tahoe (Glenn Miller, University of Nevada, Reno, unpub. data). In fact, Allen et al. (1998) calculated that while using only 11-12% of the total fuel used for Lake Tahoe boating, these engines contributed 90% of the MTBE to the water. In contrast the 4-stroke engines consumed 87% of the fuel and but were responsible for only 8% of the estimated MTBE loading to the lake from all marine engines.

The results of these cumulative studies resulted in regulations imposed by the Tahoe Regional Planning Agency (TRPA), banning certain two stroke engine technologies. This ban took effect on June 1, 1999. Additionally, several large oil companies began producing gasoline without MTBE and delivering it to the south end of the lake. With both programs to abate MTBE loading to the lake and groundwater in place by late spring of 1999, the summer boating season was expected to produce lower levels of in-lake fuel constituents. The TRG began sampling in August to evaluate the effectiveness of these changes, i.e. comparison of lake concentrations of MTBE and BTEX in the summer of 1999 relative to 1997 and 1998.

METHODS

Sampling locations were selected to describe changes in MTBE and BTEX concentration in Lake Tahoe that may have resulted from the policy decisions above. Therefore, our sampling focused on locations which had positive results during the 1997 and 1998 monitoring. Site selection was separated into three categories; 1) an open water, midlake location where boating is minimal, 2) nearshore, at 10 locations around the perimeter of the lake, where the majority of boat occurs, and 3) 10 locations on the south shore where boat traffic is concentrated ("hot spots"), often associated with launch ramps, refueling facilities, marinas or a combination of the above. Within each category, specific sites were chosen, whenever possible, to replicate those sampled in previous years.

The timing of the sampling, late August and the Labor Day weekend in September, coincided with the peak of the summer boating season. Three sampling dates were chosen, mid-week (Wednesday and Thursday, 25 and 26 August, respectively). Weekend samples were collected on Monday (30 August), and the Labor Day weekend was represented by samples taken on the Tuesday after the holiday (7 September).

At all locations, with the exception of mid-lake, water samples were taken by hand at a depth of 0.5 m. Our previous sampling at Lake Tahoe showed this to be a representative depth for the nearshore stations. The closed VOA vials were submerged to the sampling depth and then opened and allowed to fill completely. The cap was replaced while submerged. Samples were checked to ensure no air space remained within the VOA vial before they were placed on ice in a cooler. The mid-lake samples were collected using a 1.2 L, stainless Kemmerer well sampler with Teflon end caps. The sampler was lowered to depth and closed with a messenger. Water was then transferred to the VOA vial and filled so that no air spaces remained. All samples were kept on ice from collection through transport to Lawrence Livermore National Laboratories (LLNL). All analytical determinations were made by LLNL staff at their facilities (C. Koester, pers. comm.)

RESULTS

Open water and nearshore samples showed a significant decrease in MTBE concentration when compared to data collected in 1997 and 1998. Generally, ambient concentrations decreased by a factor of 10 with samples around the north end of the lake (Homewood to Glenbrook) at or below the 0.06 μg/L level of detection. Samples collected in the vicinity of the south end of the lake (Zephyr Cove to Emerald Bay) showed a similar drop in concentration from previous years, but remained above the level of detection at a few tenths of a part per billion (μg/L). Ambient concentrations of the BTEX compounds (benzene, toluene, ethylbenzene, and xylene) at the nearshore locations were also found to be lower than levels recorded in the past two years of monitoring (Table 1).

Samples from the "hot spot" locations had greater MTBE levels than the nearshore and open water areas; four concentrations approached or exceeded drinking water standards. The remaining six "hot spots" had fuel concentrations similar to nearshore areas sampled during the 1997 and 1998 monitoring. At the four "hot spots" where fuel constituent concentrations neared or exceeded drinking water standards, MTBE and

BTEX concentrations were highly variable. MTBE concentrations ranged from 0.46 $\mu g/L$ up to 56.5 $\mu g/L$. This high value is over four times the primary drinking water standard of 13 $\mu g/L$. The dramatic difference in results between these "hot spots" and the remainder of the lake suggests source contamination has not been completely eliminated by actions to date, but that inputs to the lake were significantly reduced in the summer of 1999.

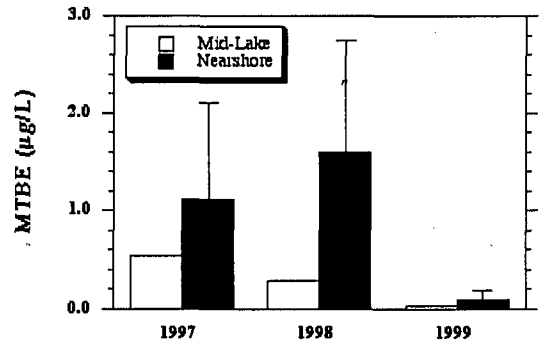
DISCUSSION

The sampling dates selected during this study were at the end of the summer boating season during the month of August and after the Labor Day weekend early in September. Allen et al. (1998) showed this period representative of high MTBE and BTEX concentrations in Lake Tahoe. With the exception of a few of the "hot spots", the data collected during this study showed little variation between sampling dates.

Comparisons of data collected during this study with that of previous years shows a dramatic decrease in MTBE concentration at both offshore and nearshore locations (86.7% and 95.8%, respectively)(Figure 1). This demonstrates that programs to eliminate MTBE from Lake Tahoe are having an effect. The offshore and most of the nearshore locations around the lake had MTBE concentrations at or near the analytical level of detection (LOD) throughout the sampling period

The sampling of "hot spots" around the south end of Lake Tahoe resulted in highly variable results (MTBE range <0.06 to 56.5 $\mu g/L$). MTBE samples collected at Ski Run Marina exceeded the California primary drinking water standard of 13 $\mu g/L$ by four-fold on two separate sampling dates. Additionally the California drinking water standard for benzene (0.1 $\mu g/L$) was surpassed on the post Labor Day sampling, 7 September. These samples stand out from the rest as being extremely high even for the "hot spot" locations. The reasons may be due to above average concentration of boats per unit area or some problem with operations at the facilities. The two other locations where measured concentrations of MTBE approached or exceeded California drinking water standards where associated with boat launch ramps. Since neither location is in the immediate proximity of fueling facilities it is expected that the fuel constituents came from the boats themselves. While it is unclear how the fuel entered the water, any number of human errors and boat malfunctions could have contributed. One distinct possibility associated with launch ramps is the draining of the bilge upon removal of the boat from the water. Either the intentional removal of boat plugs to allow draining while on the incline ramp or the automatic operation of electrical bilge pumps when water rushes to the back of the boat will cause fuel laden water to flow directly into the lake in the vicinity of the ramp.

CONCLUSION



On the whole, fuel constituent concentrations in Lake Tahoe are down dramatically from previous years. This could be the result of the TRPA regulation banning certain two cycle engine technologies or as a byproduct of some service stations within the Tahoe basin selling MTBE-free fuel. A comparison of the decreases in ambient MTBE and toluene concentrations was done to determine which corrective action was having the greatest impact on Tahoe water quality. If the MTBE-free fuel was having the greatest impact, the ambient MTBE concentrations would be expected to decrease while toluene concentrations in the lake remained near the levels recorded in 1997 and 1998. If the new boating regulations were having the greatest impact, both MTBE and toluene concentrations could be expected to drop. Indeed both mean MTBE and mean toluene concentrations drop significantly (95.8% and 88.3% respectively) indicating that the elimination of the highly polluting two cycle engines is having a clear impact on water quality.

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Validation of Thermal Infrared Data and Products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) over Land

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Introduction

In 1997 a proposal was submitted to the Satellite Remote Sensing Measurement Accuracy, Variability, and Validation Studies NASA Research Announcement entitled:

"Validation of Thermal Infrared Data and Products from MODIS and ASTER over Land"

The objective of the proposal was to validate the thermal infrared data and products acquired over land from the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS) using a set of automated validation sites. The main advantage of this approach is the validation data are acquired automatically allowing validation whenever satellite data are acquired and monitoring of accuracy and precision of the satellite data and products over time. The proposal was accepted and four automated validation sites were identified throughout the world. Lake Tahoe was identified as one of the sites for several reasons:

Large size. High elevation. Does not freeze in winter. Excellent logistical support.

The large size permits validation of sensors with large footprints; for example ASTER has a footprint size of 90 m while MODIS has a footprint size of 1 km. The high elevation minimizes any errors associated with propagation of the ground measurements through the atmosphere for comparison with the satellite instrument measurements. The lack of freezing allows validation throughout the year and coupled with the excellent logistical support from the Tahoe Research Group has allowed us to install a comprehensive set of measuring devices allowing year-round validation of thermal infrared data from satellite as well as aircraft instruments.

Measurements

To characterize the radiative and bulk temperatures of Lake Tahoe, four rafts have been deployed arranged in a box centered on the Lake. Each raft has a radiometer and several temperature loggers (Figure 1). The data from the temperature probes and radiometer is stored on a solar powered data logger. The logger has cellular access and the data are downloaded to NASA/JPL automatically on a daily basis. Measurements of the radiative and bulk temperatures are made every 2.5 minutes.

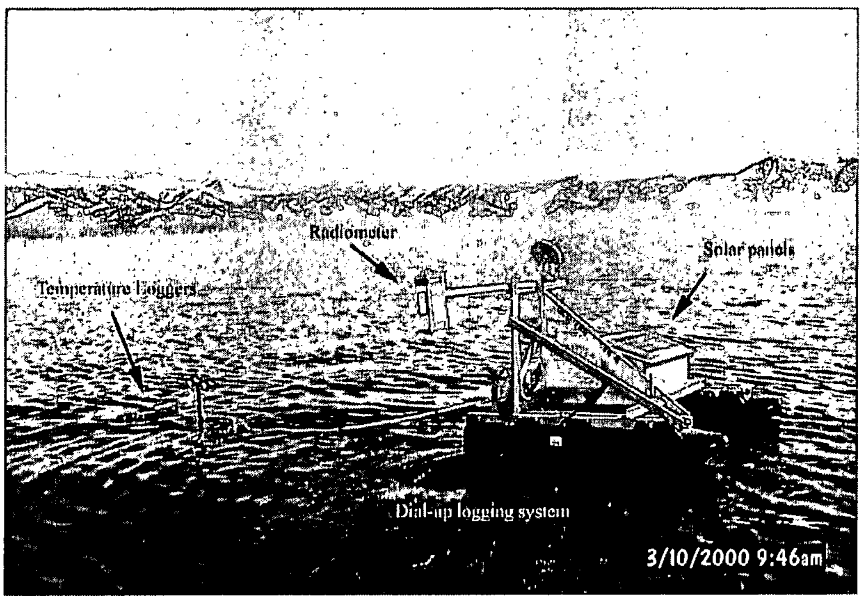

Figure 1. Mk IV raft at L. Tahoe with double solar panels, radiometer and temperature loggers on thermistor chain.

In order to perform a comparison with the satellite data it is necessary to measure the bulk and radiative temperatures and also characterize the atmosphere between the surface and the satellite. This has necessitated the installation of additional atmospheric monitoring equipment that supplements the measurements already being made at the US Coast Guard station (Figure 2). The additional measurements include a Total Sky Imager (TSI) and Multi Filter Rotating Shadowband Radiometer (MFRSR). The TSI takes an image of the sky every couple of minutes allowing us to determine the amount of cloud present and the MFRSR provides information on the amount and types of particles (aerosols) in the air as well as the total column water vapor.

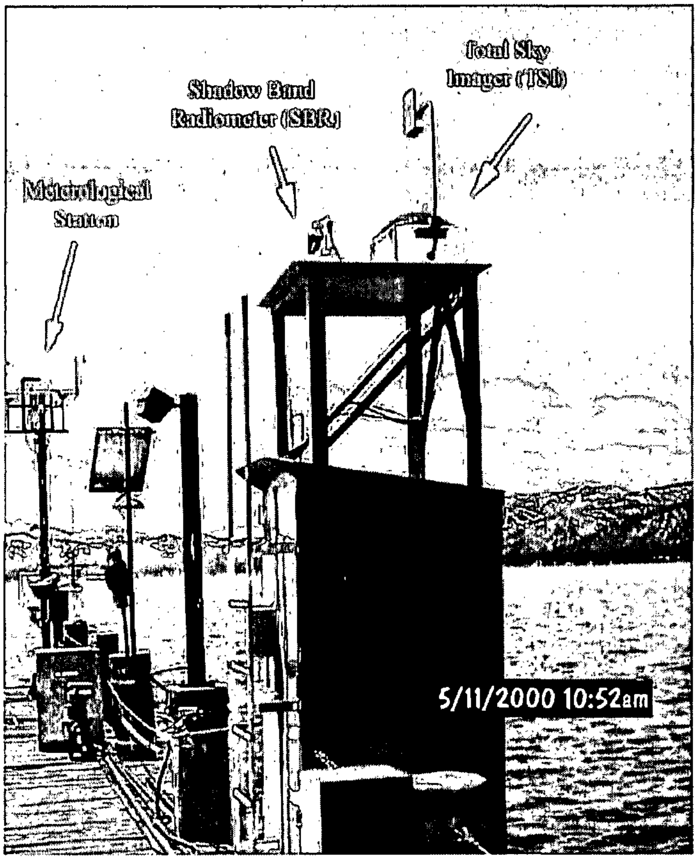

Figure 2. A YankeeTotal Sky Imager (TSI) and Yankee Multi Filter Rotating Shadowband Radiometer (MFRSR) on new mount above gauging station.

Early Science Results

The primary objective of this proposal is to validate the thermal infrared data and products from the MODIS and ASTER sensors on the Terra platform. The Terra platform was launched in December 1999 but, due to technical difficulties, did not reach orbit until several months later. As a result, data suitable for validation are only just becoming available.

In the interim, the data from the site is being used to validate other satellite and airborne sensors. Below is an example of some results from validation work involving a spaceborne instrument: the Landsat Enhanced Thematic Mapper (ETM+).

Landsat ETM+ was launched approximately 7 months prior to the launch of Terra and thus validation data are available over the annual skin temperature cycle at Lake Tahoe (~5 — 25 ° C). The temperature data from Lake Tahoe were provided to F. Palluconi (Landsat Science Team member) and used by Palluconi to validate the thermal infrared channel of Landsat ETM+. The results are summarized in Figure 3 and indicate a substantial error of approximately 2.5-3 degrees in the calibration of the Landsat thermal channel 6. While this error is clearly serious, it appears to be constant over time and temperature (Figure 3). Therefore it should be possible to update the calibration constants at the data processing center so that subsequent datasets are better calibrated or provide a correction algorithm for users. It should be emphasized that while the error appears nearly constant over time and temperature at present, it could change due to some change in the instrument and therefore requires further monitoring.

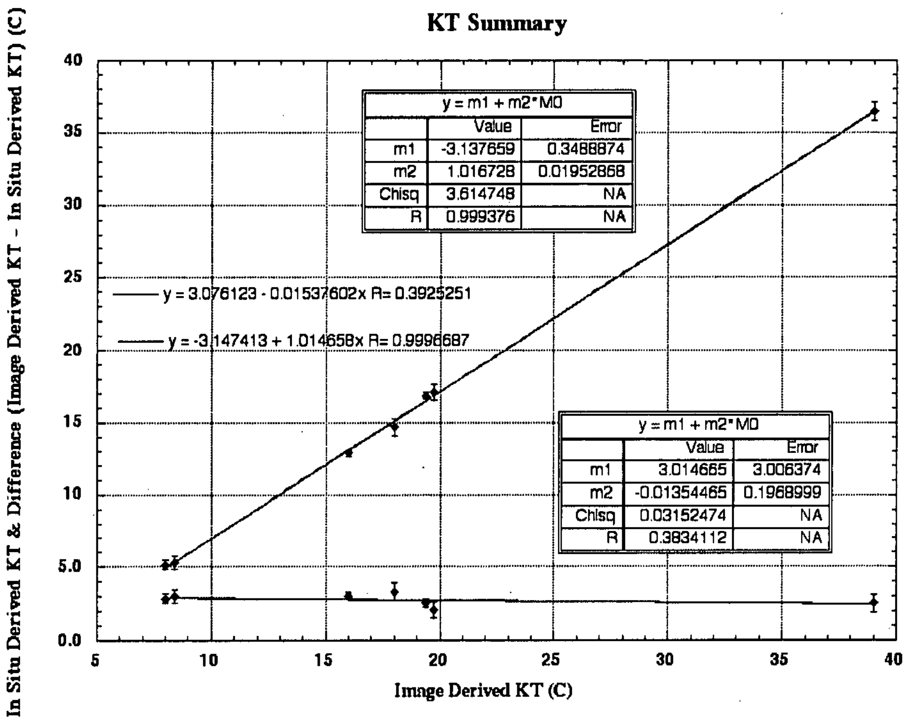

Figure 3 In Situ Derived Kinetic Temperature and Kinetic Temperature Difference (Image derived minus In situ) versus Image Derived Kinetic Temperature. (Plot courtesy of F. Palluconi)

Future Plans

Obviously future work is focused primarily on the validation of the ASTER and MODIS data. Work is also underway to add additional measurement capability at both the rafts and the US Coast Guard Station. A full meteorological station providing wind speed, wind direction, relative humidity and net radiation, that can be deployed on a floating platform, has been purchased and will be installed on one of the rafts in the fall of 2000. These data will be valuable not only in validating the satellite data but also in understanding the lake climatology. An upward looking radiometer has also been added to the US Coast Guard Station that provides information on changes in the temperature of the sky with angle.

Recent Publications and Media

Hook, S. J. 1998. In Flight Validation of Thermal Infrared Data over Land. European Symposium on Remote Sensing: SENSORS, SYSTEMS AND NEXT GENERATION SATELLITES IV, Barcelona, Spain, September 21-25. (Abstract).

Hook, S. J., Myers, J. J., Thome, K. J., Fitzgerald, M. and A. B. Kahle, 1999. The MODIS/ASTER Airborne Simulator (MASTER) — A New Instrument for Earth Science Studies. Accepted Remote Sensing of Environment.

Hook, S. J., Schladow, G., Abtahi, A. F. Prata and B. Richards. In-Flight Validation of Remotely Sensed Thermal Infrared Data for Hydrological Applications. American Geophyscial Union, San Francisco. (Abstract)

Hook, S. J., G. Schladow, A. Abtahi, F. Prata, B. Richards and S. Palmarsson. Validation of ASTER and MODIS Thermal Infrared Products. Sixth International Conference Remote Sensing for Marine and Coastal Environments. Charleston, South Carolina, May 1-3 2000. (Abstract)

Hook, S. J. 2000. MASTER — A New Instrument for Hyperspectral Analysis from the Visible to Thermal Infrared. 2nd EARSeL Workshop on Hyperspectral Imaging, Enschede, The Netherlands, July 11-13. (Abstract).

Tahoe World January 13 2000. 1.3 billion satellite links Tahoe to NASA ***By Shannon Darling, Tahoe World Staff.***

Tahoe World March 10, 2000. NASA rafts await satellite data ***By Shannon Darling, Tahoe World Staff.***

HomePage

Assessing potential for spread and impacts of Eurasian watermilfoil *Myriophyllum spicatum*) in Lake Tahoe using *in situ* transplants, microcosms, and bioassays

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Introduction

This project was conducted to determine the ecosystem effects of the invasion of Eurasian watermilfoil (*Myriophyllum spicatum*) at Lake Tahoe and compare these effects to the native plant, *Elodea canadensis*. Submersed macrophytes, such as these, have been shown to link littoral sediments with the overlying water column by releasing nutrients, such as nitrogen and phosphorus, that contribute to the process of eutrophication (Barko et al., 1991, Jackson et al., 1994, James et al, 1996, Barko and James, 1998). The majority of these studies have been conducted in mesotrophic and eutrophic systems, leaving a paucity of research in ultra-oligotrophic systems, such as Lake Tahoe. The invasion of *M. spicatum* in Lake Tahoe is of great concern to those that value the uniquely pristine ultra-oligotrophic environment because of its potential to impair water quality and change the sensitive nutrient cycles of the littoral ecosystem.

Objectives

Monitor the occurrence and spread of *M. spicatum* around Lake Tahoe. Estimate the potential for infestation of new areas around the lake Determine relative threates of *M. spicatum* and *E. canadensis* to lake water quality through the release of nutrients and enhancement of algae growth.

Approach and Methods

Lake Surveys (Objective 1)

We conducted aerial, boat, and SCUBA surveys to monitor the current distribution of M. spicatum populations around Lake Tahoe (Fig. 1). We established 35-meter transects across plant communities at four locations: Meeks Bay, Emerald Bay, Crystal Bay Marina, and Obexer's Marina. Along each transect, 10 permanent sampling sites were surveyed four times over the plant's growing season (July, August, September, Oct-November, 1999) to monitor changes in density of M. spicatum.

Reciprocal transplant (Objective 2)

Apical meristems of *M. spicatum* (20-cm length) were collected from Cove East Lagoon and Meeks Bay Marina on August 21, 1999 and planted into (1-gallon) acid-washed plastic containers filled with sediment from various Lake Tahoe sites. We used the following reciprocal transplant design to combine sources of sediment, sources of plants, and growth locations:

Five cuttings with apical tips were placed in a container, and each treatment (Site-plant source-sediment source) was replicated four times. Containers were placed on the bottom of the lake at depths of 10-12 feet. Following nine weeks of growth, containers were removed from the transplant sites on October 23, 1999. Plant survivorship and growth were determined (% survivorship and plant height).

^{32}*P cycling in hydroponic microcosms* (Objective 3)

Apical meristems of *M. spicatum* (20cm, without roots) and *E. canadensis* (with a few roots) were planted in containers of sediment in the Tahoe Keys East Cove Lagoon on August 24, 1999 and left to establish roots for 12 days prior to transfer to laboratory microcosm tubes. Plants were grown hydroponically in filtered lake water microcosms for 45 days. Glass root compartments held 135 ml of filtered lake water with a 10 μ Ci addition of carrier free $^{32}P\text{-}PO_3^{4-}$. Microcosm treatments consisted of one plant per tube: *M. spicatum* (^{32}P, n=10), *E. canadensis* (^{32}P, n=9), *M. spicatum* (no ^{32}P, n=10), and filtered water (no plants, no ^{32}P, n=6). Treatments were split randomly into two separate growth chambers with long (14 hr)- and short-day (10hr) photoperiods. Temperature and light levels were maintained equally in both chambers at ~18° C and 275 μ mol respectively. We stirred water columns and sampled 1-ml for liquid scintillation counting (LSC) 36 days of the 45-day experimental period (September 9, 1999 to October 20, 1999) to monitor leakage of $^{32}PO_3^{4-}$ from plant shoots during growth and senescence. The activity in root compartments was sampled at the start of the experiment (September 9, 1999), on September 15, 1999, and at the end of the experiment (October 20, 1999). We filtered suspended particulate matter in the water columns on the final day of the experiment to determine how much ^{32}P was associated with plankton and detritus.

Outdoor sediment-plant microcosms and ^{14}*C phytoplankton bioassay* (Objective 3)

We established microcosms of *M. spicatum* (n=5) and *E. canadensis* (n=5) in clear, Plexiglas tubes (1.5 liters) using lake sediment from the Tahoe Keys and unfiltered lake water from near Tahoe City (see map) on September 24, 1999. Two types of controls without plants included (1) tubes with lake sediment and unfiltered lake water (n=5), and (2) tubes with unfiltered lake water alone (n=4). Initial sediment and water were sample from microcosms for nutrient and chlorophyll-*a* analyses. Following a five-week growth period outside, under natural photoperiod and temperature regime, sediments and water were collected from individual microcosms for nutrient and chlorophyll-*a* analyses.

Water from microcosms was composited by treatment and filtered through HA Millipore® membrane filters for use in a bioassay to test the response of natural phytoplankton populations to filtered exudates from microcosms treatments. A small amount of radioactive tracer $^{14}C\text{-}NaHCO_3$ was mixed into lake water containing natural phytoplankton we added filtered water containing exudates from the sediment-plant microcosms in concentrations of 1% and 10% to bioassay flasks. An additional set of control flasks included deionized water (DI) at 1% and 10% concentration. All treatments were in triplicate, except the DI controls. The flasks were placed in a laboratory incubator under fluorescent lighting (275 µ mol) at ambient lake temperature (15°C) and day length (10 hours). The growth response of phytoplankton was measured every two days over a 6-day period according to *in vivo* fluorescence and ^{14}C radioactivity accumulated in phytoplankton filtered onto HA Millipore® membrane filters (Goldman, 1968).

Results and Discussion

Reciprocal transplant (Objective 2)

Myriophyllum spicatum grew successfully at every site and in each type of sediment, except at Boatworks Marina under extreme wave conditions (Fig. 2). Survivorship was highest when plants from a particular location were grown at that location. Crayfish preferentially grazed foreign transplants. *Myriophyllum spicatum* grew taller at the Tahoe Keys, the greatest source of *M. spicatum* at Lake Tahoe, than at any of the other lake sites. At every site, *M. spicatum* grew taller in sediment from the Tahoe Keys than in sediment from any other source.

^{32}P cycling in hydroponic microcosms (Objective 3)

At the end of the experiment, up to 0.45% of the original amount of ^{32}P introduced into sealed root compartments of *M. spicatum* was released into the water columns, while less than 0.05 % was released into the water columns of *E. canadensis* microcosms (Fig. 3). Photoperiod did not affect the release of ^{32}P. ^{32}P activities in the water of root compartments were greater in jars containing *M. spicatum* than *E. canadensis* on the mid-experiment sampling date (September 15, 1999) (t=3.613, p = .0010), suggesting greater uptake of ^{32}P by *E. canadensis* plants. ^{32}P associated with suspended particulate matter (SPM) in water columns was not significantly greater in *M. spicatum* microcosms than *E. canadensis* (ANOVA, $F = 3.6411_{1,18}$, $p = .0725$). These results suggest that regardless of photoperiod, the invasive macrophyte, *M. spicatum*, releases phosphorus into the water column during growth and senescence to a greater extent than the native plant, *E. canadensis*, thereby contributing a nutrient source for algal growth.

Outdoor sediment-plant microcosms and ^{14}C Phytoplankton Bioassay (Objective 3)

Chlorophyll-*a* was greater in outdoor microcosms with *M. spicatum* than in the initial lake water, *E. canadensis* microcosms, and control microcosms. Total phosphorus was greater in the water of microcosms containing *M. spicatum* than in microcosms with *E. canadensis*, sediment, and lake water. NO_3 concentrations were greater in the initial unfiltered lake water and in microcosms with *M. spicatum*, than in microcosms with *E. canadensis*, sediment or lake water. There was not enough information to distinguish effects of microcosm treatments on water nutrients, SRP, NH4, and DP, or on sediment nutrients, TKN and Olsen-P.

In all bioassay treatment flasks, *in vivo* chlorophyll measurements and ^{14}C counts on HA Millipore membrane filters indicated that phytoplankton populations increased over the six-day incubation period. At the 10% filtered exudate dilution level, the *M. spicatum* treatment yielded higher *in vivo* fluorescence in bioassay flasks than *E. canadensis* and the control treatments. Similarly, *E. canadensis* exudates enhanced phytoplankton productivity as measured by *in vivo* fluorescence more than the control treatments. Phytoplankton productivity measured by ^{14}C-uptake was greater in flasks with *M. spicatum* exudates than flasks with *E. canadensis* exudates. Exudates from both *M. spicatum* and *E. canadensis* enhanced phytoplankton growth more than the no-plant controls (sediment, lake water, and deionized water). It is possible that high TP and NO_3 levels from the sediment-plant microcosms were responsible for increased phytoplankton productivity. However, future studies should consider more detailed chemical analyses of plant exudates including dissolved organic carbon and secondary compounds (Wetzel, 1975, Gross et al., 1996, Wetzel and Sondergaard, 1998). These results suggest that the invasive plant, *M. spicatum* may have a more negative affect on water quality at Lake Tahoe than *E. canadensis*.

Conclusions

M. spicatum populations are expanding around Lake Tahoe and have a potential to establish in protected sites where it is not yet present. Despite the greater capacity of *E. canadensis* to acquire ^{32}P in its tissues, release of ^{32}P into the water columns appears to have been greater in microcosms with *M. spicatum* than microcosms with *E. canadensis*. Although results were marginally significant, we detected higher levels of ^{32}P in suspended particulate matter of the hydroponic *M. spicatum* microcosms, suggesting some uptake of ^{32}P by phytoplankton and bacterioplankton in the water column. Similarly, the outdoor sediment-plant microcosms demonstrated higher chlorophyll-*a* levels in water where *M. spicatum* grew than in water with *E. canadensis* or control treatments without plants. Furthermore, filtered exudates from *M. spicatum* microcosms enhanced productivity of mid-lake natural phytoplankton in ^{14}C bioassays more than *E. canadensis* or filtered sediment and lake water from control microcosms. Both the *in vivo* chlorophyll-*a* and ^{14}C-uptake responses of natural phytoplankton productivity in this bioassay support the hypothesis that *M. spicatum* accelerates growth of phytoplankton at Lake Tahoe more than the native plant, *E. canadensis*. Results of this study suggest that in late summer, the invasive macrophyte, *M. spicatum*, contributes to a loss of water quality in ultra-oligotrophic Lake Tahoe to a greater extent than the native plant, *E. canadensis*, by releasing nutrients into the water column and enhancing the productivity of phytoplankton.

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Atmospheric Lead and Mercury Deposition at Lake Tahoe

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Abstract

Evidence from this study suggests the existence of a significant modern source for atmospheric Hg deposition in the Sierra Nevada. Concentrations of both lead (Pb) and mercury (Hg) in the sediments of Lake Tahoe deposited prior to 1850 are similar to concentrations in the catchment bedrock, but their concentrations in modern sediments have increased six-fold for Pb (average 83 ppm) and five-fold for Hg (average 0.191 ppm). The lake occupies a relatively pristine, non-industrialized subalpine basin, with a watershed to lake surface ratio of only 1.6. Excess accumulation of trace metals in these sediments should closely reflect direct atmospheric deposition. On average, since 1980 there have been approximately 17 mg of Pb and 38 μg of Hg deposited annually per square meter in excess of the baseline flux. While Pb emissions have occurred locally in the Tahoe basin, from combustion of leaded gasoline until about 1985, the deposition of atmospheric Hg must represent a predominately regional to global source of contamination. Ratios of total modern flux to preindustrial flux are 29 for Pb and 24 for Hg. The flux ratio for Pb is somewhat higher than reported from the eastern USA and Canada, but is not atypical. The flux ratio for Hg is much higher than that observed in most other natural aquatic systems without point-source contamination. Both orographic scavenging and cold-condensation processes could enhance the deposition of Hg and other atmospheric pollutants over the Sierra Nevada.

Introduction

Modern industrial processes, product distribution, and material consumption patterns all disperse a wide variety of toxic metals into the environment. Of particular concern is the atmospheric emission of these metals, which can cause significant contamination over large areas. The introduction of alkyl-leaded gasoline in 1923, for example, ultimately produced a global anthropogenic Pb emission rate that exceeded the total contribution from natural sources by a factor of 28 (*1*). Mercury emission rates have also increased over modern times, and Hg is now listed as an EPA priority pollutant, in large part due to concerns about its biomagnification in aquatic food chains.

To date, there have been few studies of atmospheric deposition for trace metals on the U.S west coast. This study looks at the history of atmospheric Hg deposition over Lake Tahoe, a relatively pristine watershed in the Sierra Nevada mountains of California and Nevada. While there has never been any recorded use of Hg in the Tahoe basin, there was a substantial production and consumption of Hg in mining districts of California and Nevada adjacent to the Tahoe basin during the late 1800s. Our objective was to compare the modern rates of Hg deposition to the preindustrial (baseline) rates, as reconstructed from lake sediment cores. We also examined Pb accumulation rates, and compared the results for both

Pb and Hg to sediment concentrations and to flux estimates from similar studies in other regions of North America. The sediment concentrations of titanium (Ti), a conservative reference element, were used as correction factors in reconstructing these trace metal deposition rates.

Study Site and Methods

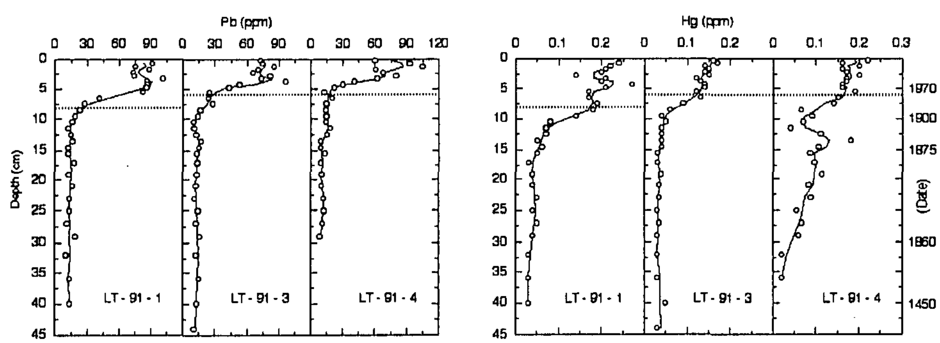
Lake Tahoe occupies a graben in the northern region of the Sierra Nevada mountains, on the border between California and Nevada. Its surface area is 498 km^2, within a natural basin of 1,311 km^2. Less than 8% of the terrestrial area is urbanized. At its natural rim the lake is 1897 meters above sea level, but surrounding mountains extend to over 3000 meters. On its western boundary the Tahoe watershed is delineated by the north-to-south bearing crest of the Sierra Nevada range.

The sediment cores examined in this study were extracted with a Soutar box corer, deployed from the U.C. Davis Research Vessel John LeConte. Two box cores (LT-91-1 and LT-91-3) were extracted from opposite ends of the lake in the profundal zone below 400 meters. A third core (LT-91-4) was taken off the west shoreline on a deep shelf at 300 meters depth.

Concentrations of ^{210}Pb and ^{137}Cs were determined by alpha and gamma spectrometry, respectively, in the laboratory of Dr. David Edgington. The analyses for Pb and Ti were performed by energy dispersive x-ray spectrometry. Samples for Hg analysis were digested in nitric and sulfuric acids, under pressure, then subsequently analyzed for total Hg (THg) using a modified cold vapor atomic absorption (CVAA) micro-technique (*2*).

Results

The concentrations of Pb and Hg in each sediment section of the three cores from Lake Tahoe are shown below, along with the smoothed profiles produced by a three term moving average. The onset horizon of ^{137}Cs is indicated by a horizontal line at the bottom of the deepest sediment section in which ^{137}Cs was detected. This onset horizon is generally interpreted as representing the first appearance (1952—1954) of global fallout from the atmospheric testing of thermonuclear weapons. To facilitate interpretation, approximate dates of sediment deposition are also indicated on the vertical axis.



In all three cores, Hg concentrations increase substantially prior to the ^{137}Cs onset horizon, and prior to equivalent changes in Pb concentrations. Above the ^{137}Cs horizon, however, Hg concentrations increase more slowly, whereas Pb concentrations begin to increase rapidly until they stabilize somewhat in the surficial sediments. In contrast to Pb, the trend of increasing Hg content persists into surficial sediments, which are enriched about five-fold over the baseline concentrations (see sediment enrichment factors listed in Table 1).

Table 1. Concentrations of Pb, Hg and Ti in Lake Tahoe sediment cores; with mean values, relative standard deviations (RSD) and sediment enrichment factors (SEF) calculated for each element.

	Pb (ppm)		Hg (ppm)		Ti (wt %)		SEF		
core	surficial	baseline	surficial	baseline	surficial	baseline	Pb	Hg	Ti
LT-91-1	84.7	12.2	0.223	0.030	0.278	0.225	6.0	6.4	0.2
LT-91-3	77.1	12.5	0.157	0.037	0.260	0.259	5.2	3.3	0.0
LT-91-4	85.9	10.5	0.193	0.033	0.306	0.284	7.2	4.8	0.1
mean	82.6	11.7	0.191	0.033	0.281	0.256	6.1	4.9	0.1
RSD (%)	6	9	17	10	8	12	17	32	< 1

Since it has been shown that redox conditions do not appreciably influence the structure of Pb or Hg stratigraphy in most lake sediments (*3*), we interpret these patterns in the Tahoe sediments as representing temporal changes in Pb and Hg loading rates. These patterns do not change significantly when corrected for the contribution of trace metals derived from watershed weathering (normalized by factoring to variation in the content of sediment titanium as a conservative lithogenic element in most depositional environments).

Sediment fluxes of Pb and Hg were calculated as the product of sediment concentration and mass sedimentation rate. These data are summarized for the modern (post 1980) depositional period in Table 2. For modern sediments, with equal weight given to each core, the estimate of excess (normalized) Pb flux is 17 mg m^{-2} y^{-1}. A corresponding estimate for excess Hg flux is 38 μg m^{-2} y^{-1}.

Concise representation of change in deposition rate over time within a system is given by the flux ratio. This is simply the modern flux divided by a baseline, or preindustrial (ante 1850) flux. Like SEF factors this flux ratio must be calculated from the total (i.e., non-normalized) concentrations. Flux ratios are independent of most factors that affect Hg concentrations, such as site conditions, sediment focusing, and site-specific differences in absolute rates of atmospheric Hg deposition. Thus, flux ratios provide a unitless measure for the comparison of changes in Hg deposition between sites and geographic regions. At 47 μg m^{-2} y^{-1} the average modern flux of Hg (uncorrected) to Lake Tahoe sediments is 24 times greater than the baseline flux was prior to 1850 (2.0 μg m^{-2} y^{-1}). This flux ratio is substantially higher than observed in the eastern and midwestern U.S. or in Alaska and Canada (*4*). Neither the modern flux nor the preindustrial flux at Lake Tahoe, however, fall outside the range of results found in other studies. Thus, it appears that high flux ratios for Hg in the Tahoe sediments result from a combination of relatively low preindustrial flux and a comparatively high modern flux.

For Pb, the average modern flux (uncorrected) to Lake Tahoe sediments is 20 mg m^{-2} y^{-1}, and the average preindustrial accumulation rate is 0.7 mg m^{-2} y^{-1}. These values and the resulting flux ratio of 29 are similar to Pb accumulation rates found at other sites around the country (*4*).

Since Hg is known to bioaccumulate in aquatic food chains, and since Hg flux to the sediments of Lake Tahoe has increased substantially over the last 100 years, we obtained measurements of Hg content in the biota (*4*); specifically crayfish (*Pacifastacus leniusculus*), which has been recommended as a reliable indicator of trace metal contamination, and the Mackinaw trout (*Salvelinus namaycush*), which is a top aquatic predator and the basis of an important sport fishery at the lake. Several individuals of each species were collected from about one kilometer off the west shore, just south of Tahoe City. These concentrations are reported in ppm ($\mu g\ g^{-1}$), wet weight. The regressions show a trend of increasing Hg content with size of individuals for both Mackinaw trout and crayfish. All concentrations reported in this study, however, fall below the California state threshold of 0.5 ppm.

Discussion

One of the more interesting findings of this study is that Hg flux on the U.S. continental west coast near the crest of the Sierra Nevada mountains may be equivalent to or greater than rates of Hg deposition observed in the Midwest and eastern U.S. or in Alaska and Canada (*4*). Since there are no significant local sources of Hg emission within the Tahoe Basin, it would appear that air parcels coming off the Pacific Ocean must either carry Hg from distant sources or entrain Hg from regional sources on the west coast.

For Pb there has been a local source of historical emissions at Lake Tahoe, in the form of leaded gasoline consumption. Interestingly, this can provide some validation for the relatively high rate of modern Hg deposition estimated for this site. We have calculated automotive Pb emissions at Lake Tahoe for 1976, using fuel consumption records as estimated by in-basin gasoline sales (*5*). These calculations suggest that sufficient Pb was emitted locally to account for most of the Pb burden measured in recent sediments of the lake. Furthermore, our baseline flux of Pb to Tahoe sediments (0.7 mg $m^{-2}\ y^{-1}$) is quite similar to Pb deposition measured at a remote Sierran site (*6*), and is just slightly greater than the flux of 0.5 mg Pb $m^{-2}\ y^{-1}$ measured in bulk precipitation over the eastern central (33—48°N) Pacific Ocean (*7*).

The fact that we can accurately account for Pb burden in the Tahoe sediments, along with its general correspondence to loading rates and flux ratios observed in other studies, suggests that our reconstruction of historical sediment and trace metal deposition in this system is reliable. It is likely that Hg has been brought into the basin by prevailing westerly winds, but that Pb has been predominately contributed by automobile emissions distributed around the lake.

The unexpectedly high rate of Hg deposition observed at Tahoe in the modern sediments may occur as a result of efficient orographic scavenging by rain and snow as air parcels travel over the crest of the Sierra Nevada mountain range. Another factor that could significantly enhance Hg deposition over the Tahoe area is a process of cold-condensation, whereby temperature dependent partitioning and transport increase the concentrations of semi-volatile compounds over cooler environments (*8*). It has been shown that these processes and increased precipitation sharply enhance the accumulation of semi-volatile compounds at elevations above 2000 meters (*9*). This could increase the Hg accumulation rates over high altitude environments like Lake Tahoe, especially when there are regional downwind sources of Hg in a warmer climate at lower elevations.

Although USEPA region IX (California, Nevada and Arizona) is the second lowest of all regions in this country for estimated THg emissions (*10*), it is possible that air parcels traveling toward Tahoe could entrain Hg volatilized from the waste of historical gold and silver mining. A tremendous amount of elemental Hg was consumed during the late 1800s at several mining districts regionally close to the Tahoe basin. Somewhat surprisingly, these historical emissions from the western Sierra foothills and from Virginia City in Nevada did not produce an unequivocal signal in Lake Tahoe sediments. Elevated concentrations of Hg are found at depth in the west lake core, but do not appear in the south lake core and are significantly modulated in the north lake core. We suggest that high mass sedimentation rates from Comstock logging in the late 1800s diluted most of this historical Hg signal in the two midlake cores (*4*). For that reason we have focused this study on comparing the preindustrial Hg deposition rates to modern rates.

Much of the Hg lost to mining spoils or deposited locally during the mining era would continue to volatilize from depositional surfaces and may gradually be transported downwind across the landscape. Nriagu (*11*) suggested that re-emission of only 0.2% of Hg lost during the historical mining era in the Sierras would be equivalent to a substantial fraction of current annual anthropogenic emissions in the U.S. This continuous volatilization of Hg° from mining spoils and abandoned Hg mines in the Coastal Range, in conjunction with orographic precipitation, scavenging and cold-condensation, could be contributing to the relatively high rate of modern atmospheric Hg deposition at Lake Tahoe.

We still cannot say yet whether that Hg input derives predominately from regional, perhaps historical, sources on the west coast or from globally distributed atmospheric Hg, but the regional sources are suspect for up to 85% of THg deposition. Obviously, a series of sediment sampling transects or deposition monitoring stations are needed across both elevational and latitudinal gradients in the western U.S. to clarify the relative importance of these sources and processes.

Acknowledgements

Financial support for this research came from the Center for Ecological Health Research at the University of California—Davis (UCD) and from the Tahoe Regional Planning Agency. Peter Schiffman and Sarah Roeske in the Geology Department at UCD provided technical advice and assistance on XRF analyses. Bob Richards, Scott Hackley, Mark Palmer and Brant Allen of the UCD Tahoe Research Group helped with the sample collection. David Edgington at the University of Wisconsin—Milwaukee Center for Great Lakes Studies supplied the ^{210}Pb data and informative discussion on its interpretation. Shaun Ayers in the UCD Limnology Group performed the Hg analyses and QA/QC. We acknowledge the useful comments of three anonymous reviewers. Expanded text for most of this report can be reviewed as accepted for publication in the journal of Environmental Science and Technology (year 2000) under the title Paleolimnological Reconstruction of Historical Atmospheric Lead and Mercury Deposition at Lake Tahoe, California—Nevada.

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Kokanee and Mysids Influence on Zooplankton

Dynamics and Nutrients Recycling in Lake Tahoe

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The introductions of mysids and kokanee coincided with dramatic changes in species compositio abundance, and dynamics of the zooplankton populations, and these changes have persisted over 30 years (Richards et al. 1991). Zooplankton changes have presumably affected the lower trophic (primary productivity and water quality) and the higher trophic levels (native and sport fishes) of Tahoe. The goal for studying kokanee and mysids was to assess their predacious impacts on the p copepod community and understand their possible role in Lake Tahoe nutrient cycles. Nutrient re by biological organisms can play a large role in the productivity of oligotrophic lakes (Carpenter Kitchell 1993).

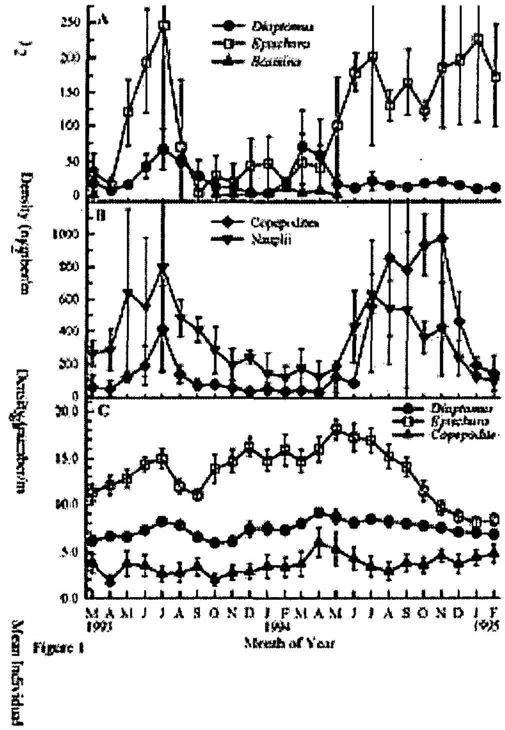

Figure 1

How external nutrient loading and internal physical events affect the nutrient cycles of Tahoe are better understood (many works b TRG) than the impact of nutrient recycling biological organisms, for example kokanee mysids. Objectives are:

- Examine the temporal dynamics of zooplankton from March 1993 to Fel 1995.
- Estimate zooplankton consumption c by kokanee and mysids then, for the time period, compare to the temporal supply estimating the predation impa kokanee and mysids.
- Estimate nitrogen and phosphorus re by kokanee and mysids then compar annual nutrient load estimating the importance of kokanee and mysids n recycling.

Zooplankton dynamics

Zooplankton have been sampled at approximately 10 day intervals from an index station in Lake for close to three decades. The March 1993 to February 1995 samples were analyzed to estimate zooplankton densities and biomass present in the Lake Tahoe. Also, production for zooplankton estimated using an empirical relationship (Stockwell and Johannsson 1997).

The copepod populations, dominating the zooplankton community, in Lake Tahoe exhibited year differences in density and dynamics with seasonal fluctuations over the two-year study period (Fi 1A). Copepod density generally peaked during the summer and was lowest during fall and winter *Epischura* adults generally were in higher densities than *Diaptomus* adults. Density of the copepo juvenile stage, copepodites and nauplii, followed a similar pattern as the adults (Figure 1B). Interestingly, *Bosmina* appeared in the zooplankton samples in March 1993 and fall through wint 1993-1994 (Figure 1A). Although the densities of *Bosmina* were relatively low, the appearance o *Bosmina* has been a rare event since the introduction of mysids to Lake Tahoe. Average weights individual adult copepods and copepodites maintained relatively consistent levels over the study (Figure 1C). An exception was an *Epischura* decline in average weight during the fall and winter 1994-1995.

Kokanee and mysid predation

A mass balance approach was used for the estimation of both consumption and excretion. The bioenergetic model is based on the mass energy balance equation:

Consumption = Growth + Metabolism + Feces + Urine, with consumption and metabolism primarily changing as functions of body size and temperature. *mixta* model parameters, with two modifications, of Rudstam (1989) were used to estimate mysi(consumption. Kokanee parameters were taken from Beauchamp et al. (1989). Population specific to the model include annual or seasonal change in body mass, the thermal experience of the pred: proportional prey composition, and the energy density of predators and prey. Monthly copepod consumption estimates from the bioenergetic simulations were then compared to monthly estima monthly copepod biomass and production.

Consumption on the zooplankton community by kokanee and mysids was drastically different (F 2B). Kokanee monthly consumption was always less than 1% of mysid monthly consumption. M monthly consumption peaked in August each year, with very different seasonal dynamics. Durin{ 1993-1994, mysid consumption quickly increased until the peak with a decline for the remainder year. 1994-1995 Monthly consumption was almost consistent throughout the modeled year, with mild ascent and descent around the peak. The different monthly consumption estimates for each was primarily based on the difference in individual size, but population density also played a roll

To better help understand the kokanee and mysid impact on the copepod assemblage, we divided kokanee and mysid estimated monthly consumption with copepod monthly estimates of biomass and production to achieve a consumption to biomass ratio. A ratio value equal to one for the consumption to biomass ratio indicated consumption of all the estimated biomass or production available. Kokanee consumption ratios were always smaller than 1% (<0.01), indicating little potential impact on the copepod assemblage (Figure 2C). In contrast, Mysids consumed a large proportion of zooplankton biomass and production throughout the study period, but mysid ratios were different between years and seasons (Figure 2C). Primarily, all mysid ratios for the 1993-1994 year were at or above a ratio of one, indicating consumption of all or more than all available biomass or production. In contrast, the 1994-1995 mysid ratios were primarily below a ratio of one, as a result of lower mysid consumption and higher copepod biomass. Therefore, mysid potential impact was greater during 1993-1994 than 1994-1995.

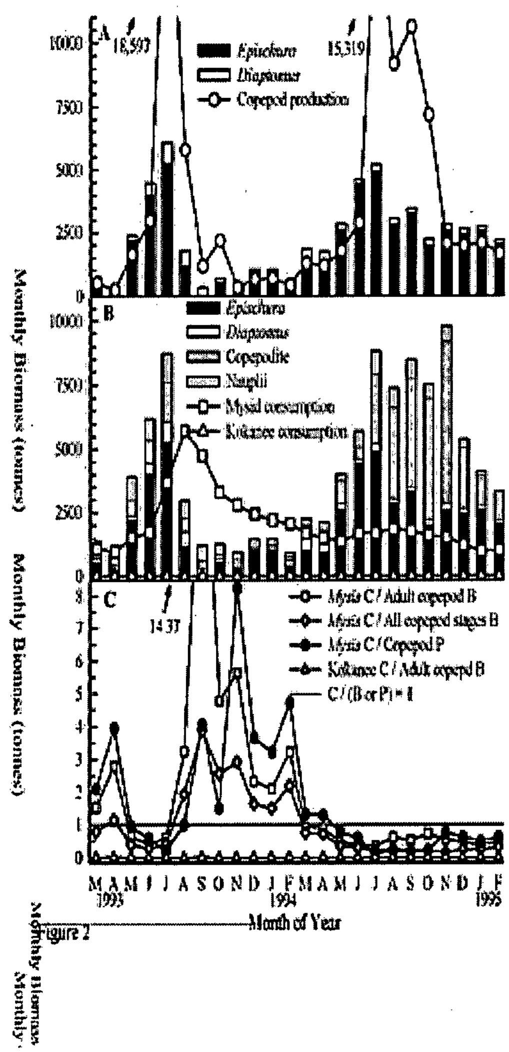

Figure 2

Kokanee and mysid excretion

Because of Lake Tahoe's sterile environment, nutrient recycling by kokanee and Mysids may be important to Lake Tahoe's nutrient cycles. A bioenergetic-based nutrient recycling model was us determine the amount of nutrients recycled by kokanee and mysids. The mass balance equation a developed by Kraft (1992) and expanded on by Schindler and Eby (1997) was used,

$$U_P = (AE_p * [P]_{food} * CONSUMP_{food}) — (GROWTH_{cons} * [P]_{cons}).$$

Where Up (g) is phosphorus excretion; AEp is the assimilation efficiency of P by the consumer; is concentration of P (g) in the prey; $CONSUMP_{food}$ is the wet mass (g) of food consumed; $GROWTH_{cons}$ is the increase in consumer wet mass (g); and $[P]_{cons}$ is the concentration of P (g) consumer. The same equation was used for nitrogen excretion. I assumed that consumers maintai stable ratio of nutrient concentrations (Sterner 1990).

Annual measurements	Mysids 1993-1994	1994-1995	Kokanee
Copepods consumption (g/m2)	64.7	36.3	0.058
Regenerated N (umol/m^2)	49,043	31,067	134
Regenerated P (umol/m^2)	998	724	4
Regenerated N:P	49	43	32
Assimilation N (umol/m^2)	6,901	2118	57
Assimilation P (umol/m^2)	326	100	5
Assimilation N:P	21	21	11
Tahoe Loading*			
DIN (umol/m^2)	19,301	19,301	19,301
SRP (umol/m^2)	588	588	588
Reg. N / DIN	254%	161%	0.70%
Reg. P / SRP	170%	123%	0.70%
Ass. N / DIN	36%	11%	0.30%
Ass. P / SRP	55%	17%	0.90%

* Jassby et al. (1994)

As with the consumption values, the mysid population recycled greater amounts of nut than the kokanee population (Table 1). Esti monthly kokanee nitrogen and phosphorus recycling averaged 11-*u*moles/m^2 ranging 1 3.5- to 21-*u*moles/m^2 and 0.4-*u*moles/m^2 r: from 0.01- to 0.9-*u*moles/m^2, respectively. kokanee nutrient recycling was small when compared to the external load to Lake Tah(0.69% of DIN and 0.72% of SRP (Table 1) Estimated mysid monthly nitrogen recyclin averaged 4086- and 2589-*u*moles/m^2 rangi: 1712- to 7486- and 1591- to 3524-*u*moles/1 during 1993-1994 and 1994-1995,

respectively; and monthly mysid phosphor recycling averaged 83- and 60-*u*moles/m^2 1 from 146- to 44- and 34- to 83-*u*moles/m^2 1993-1994 and 1994-1995, respectively (Fi Nutrients regenerated by mysids peaked du summer for both years. Mysid annual nutri recycling was important both years when compared to annual external DIN and SRP (Table 1). The average atomic nutrient rati regenerated for 1993-1994 was 49 and 199 was 43, or 22.1 and 19.4 by weight.

Sequestering of nutrients is also a way kok: and mysids may have changed the nutrient of Lake Tahoe. Again, kokanee sequestere(

nutrients was much lower than mysid (Tab. Average monthly kokanee nutrients seques was 4.8-*u*moles/m^2 ranging from 2- to 8.3-*u*moles/m^2 for nitrogen and 0.4-*u*moles ranging from 0.2- to 0.7-*u*moles/m^2 for phosphorus. For mysids, average monthly-sequestered nutrient was 575-*u*mc for N with a range of 0.0- to 1717-*u*moles/ı and 27-*u*moles/m^2 for P with a range of 0.(81-*u*moles/m^2 during 1993-1994; and 1994 mysid monthly sequestered nutrients avera; were 176-*u*moles/m^2 with a range of 22- to 625-*u*moles/m^2 and P of 8.3-*u*moles/m^2 wi range of 0.5- to 30-*u*moles/m^2 (Figure 3). / values for sequestered nutrients were less important when compared to nutrient loadi Lake Tahoe than mysid recycling (Table 1) Annual sequestered nitrogen was 36% and DIN external loading for 1993-1994 and 1994-1995, while annual sequestered phos] was 55% and 17% (Table 5). Mysids appeɛ an important source and competitor for nitı and phosphorus.

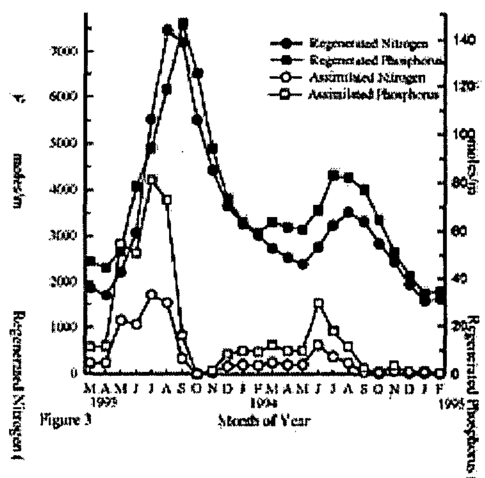

Figure 3

Conclusion

Mysids controlled the copepod population during the fall and winter of 1993-1994, and growth a limited by the availability of copepod biomass. During 1994-1995, mysid growth was greatly red compared to the previous year, but unlike the year before, the copepod populations were not limi mysid growth. Other factor may be limiting mysid growth. A possible limiting factor was food qı either stoichiometry or highly unsaturated fatty acids.

Mysid predation may have caused a cascade down the food web. When *Epischura* biomass was l to mysid predation, *Bosmina* appeared in the zooplankton samples; but during high *Epischura* biı *Bosmina* did not appear in the zooplankton samples. This interaction between mysids and *Episch* been suggested before being a factor in the population dynamics of *Bosmina* (Morgan et al. 1978 Unfortunately, food quality can not be ruled out as a factor determining the appearance of *Bosmiı*

The mysid population appears important to the nutrient cycles of Lake Tahoe. Mysid nutrient rec is greater than nutrient loading to Lake Tahoe (Table 1), but nutrients may be removed from the l Tahoe system by mysids. Because of an extensive diel-vertical-migration, mysids may act as a nı pump moving nutrients to the bottom of Lake Tahoe. The removal of nutrients by mysids would the eutrophication of Lake Tahoe might be worse than currently thought. In the very near future, be combining the mysid nutrient recycling results with a model that simulates the diel-vertical-m of mysids in Lake Tahoe. The result should give us a better understanding of the amount of nutriı mysids may be removing from the system.

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Impact of Lake Trout Predation on Prey Populationsin Lake Tahoe:

A Bioenergetics Assessment

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Introduction

Since their introduction over 100 years ago, lake trout have become established as the top predator and primary sport fish in Lake Tahoe. The lake has since undergone major changes in trophic structure with introductions of kokanee (*Oncorhynchus nerka*) in the 1940s and mysids (*Mysis relicta*) in the 1960s (Richards et al. 1975; Goldman et al. 1979). While these introductions have altered lake trout feeding ecology (Morgan et al. 1978; Richards et al. 1991), quantitative assessment of their influence on lake trout behavior, and consequently, the Lake Tahoe food web, has not been conducted. Similarly, these food web changes may affect the native fish assemblage and kokanee populations, which may have important ecological implications for the Lake Tahoe basin.

Changes in Lake Tahoe's food web also have major implications for resource managers seeking to balance human development in the basin with aesthetics, water quality, and the sport fishery. The last study to evaluate the status of the sport fishery in Lake Tahoe was initiated in 1960 (e.g. Cordone and Frantz 1966, Cordone et al. 1971). Thus, there is need for current knowledge on the population dynamics of lake trout and their trophic interactions with the associated food web to better understand and manage the production potential of this fishery.

In this study, we quantified seasonal predation rates by lake trout on individual prey types to determine if predation influenced prey population dynamics in Lake Tahoe. Specifically, we investigated how prey availability affects growth, diet, and distribution of lake trout, and conversely, how lake trout predation affects prey population dynamics.

A bioenergetics model was used to assess the effects of predation by lake trout (*Salvelinus namaycush*) on prey populations in Lake Tahoe, California-Nevada. This model was combined with seasonal diet, growth, and thermal experience of lake trout during 1992-1995 to estimate seasonal consumption by the lake trout population. These results were compared to abundance and biomass of prey populations.

Results

From spring 1992 through winter 1995, mean total annual consumption amounted to 460 metric tons (tonnes) of mysid (*Mysis relicta*), 140 tonnes of native fishes (suckers, minnows, and sculpin), 6.7 tonnes (0.13 kg/ha) of kokanee (*Oncorhynchus nerka*), 22 tonnes of lake trout, and 100 tonnes of other prey, mostly signal crayfish (*Pacifasticus leniusculus*). Consumption of kokanee varied both seasonally and annually. Predation removed an estimated 22,900 adult kokanee, or 58% of potential kokanee spawners in autumn 1992 and 33,700 kokanee or 21% of the potential spawners in autumn 1994. Consumption estimates of mysids remained similar in all three years despite considerable seasonal variability in mysid abundances. Predation removed an average of 15% (range: 7-32%) of the mysid standing stock each season. Each season, predation removed 20-48% of native adult fish biomass. Consumption rates on native fishes and signal crayfish tracked changes in the availability of native prey fish and crayfish. In general, predatory demand by lake trout represented significant, but likely sustainable, fractions of the prey population biomass in Lake Tahoe.

Conclusion

In oligotrophic systems, predation can play a significant role in determining food web structure, particularly through its influence on available forage; however, this is not always the case. Our study indicates that lake trout can have substantive effects on significant components (but not all; i.e., mysids) of the forage base (e.g., kokanee, native prey fish, signal crayfish) in Lake Tahoe, despite its status as a highly oligotrophic system. In contrast, predation is often the principal cause of mortality for cyprinids and other forage fish. This appears to be the situation in Lake Tahoe, where consumption by lake trout accounted for 20-48% of seasonal native fish biomass during the three study periods. Overall, there is no indication that current lake trout populations (>250 mm) can exert sufficient predation pressure to control mysid population size in Lake Tahoe.

Overall, this study demonstrated that lake trout predation was differentially important for populations of individual prey types. Lake trout appear to be responsible for a large proportion of native prey fish mortality, possibly contributing to substantial declines in native fish abundance during the past 30 years. Similarly, predation by lake trout may have significant effects on kokanee population fluctuations, as well as on their own recruitment (via cannibalism). While lake trout had little apparent impact on mysid biomass, mysids were the most important prey for lake trout and likely contributed to high growth in this lake trout population. Thus, mysids remain the dominant strong interactor in the Lake Tahoe food web, given their well-documented influence in this lake (Richards et al. 1975, 1991; Morgan et al. 1978; Goldman et al. 1979), and the fact that lake trout, the system's top predator, have little effect on their population dynamics.

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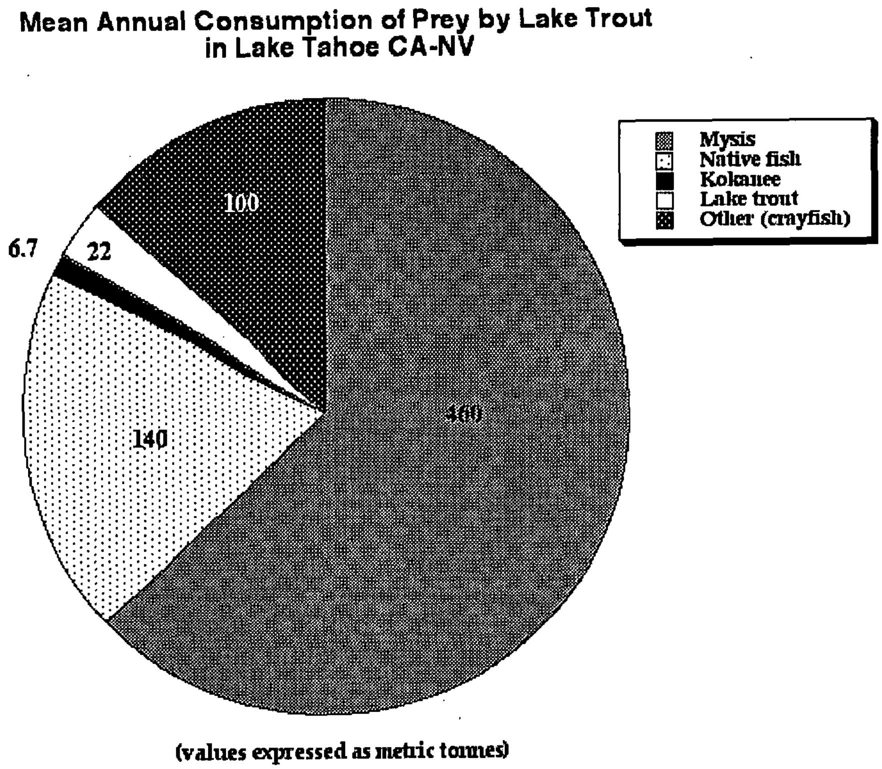
Mean Annual Consumption of Prey by Lake Trout
in Lake Tahoe CA-NV
Mysis
Native fish
Kokanee
Lake trout
Other (crayfish)
100
6.7
22
140
460
(values expressed as metric tonnes)

Developing Research

Interactions among introduced and native species in Lake Tahoe: implications for the restoration of the Lahontan cutthroat trout and current fishery management

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Introduction

Species introductions are emerging as perhaps the leading threat to aquatic ecosystem sustainability (McCann, 2000). Often accompanied by dramatic changes in food web structure and ecosystem function, these introductions are likely to have major consequences for lake management. In Lake Tahoe, understanding and predicting impacts of species introductions will greatly benefit efforts to:

manage the lake in a sustainable manner, and restore the native Lahontan cutthroat trout into the system. Past species introductions into the lake have already greatly impacted water quality and biodiversity (Goldman et al., 1979; Cordone, 1986). These introductions may also effect the sustainability of the current lake trout fishery and the potential success of cutthroat restoration efforts. Furthermore, the impending establishment of bass species recently introduced into Lake Tahoe (Lehr, 1999) could substantially disrupt the current fishery and inhibit efforts to restore the native cutthroat trout (e.g. further reducing forage fish populations, a potentially important food source for the trout). This proposed study addresses how 1) previous food web changes and 2) establishment of bass species in Lake Tahoe will effect the reintroduction of native cutthroat populations. Specifically, the objectives are to:

provide resource managers with information on the original feeding behavior of the Lahontan cutthroat trout, determine the impact of subsequent alterations to the food web which may impede current restoration efforts, and determine the impact of the newly introduced bass species on the restoration of the Lahontan cutthroat trout and Tahoe's native fishes. Often, unsuccessful species introductions could be avoided if the proper studies are conducted beforehand. The goal of this research is to provide resource managers with appropriate information on which to base cutthroat trout restoration efforts.

METHODS

In order to accomplish our objectives we will:

compare historical gill net catch data for lake trout and forage fish to current gill net catches collected in an identical fashion during the summers of 2000-2002, model the food web structure shifts in the lake at different time periods after species introductions quantify current distributions and feeding habits of largemouth and smallmouth bass. After sample collection, we will produce dynamic energy flow diagrams which we will create using stable isotope analysis on archived specimens from 1872 till present stored at the California Academy of Sciences, the U.S. National Museum (Smithsonian), and the University of Michigan Museum of Natural History.

Non-radioactive stable isotope techniques are emerging as a powerful tool for examining food web relationships (Vander Zanden, 1999). Using mass spectrometry, the ratios of heavy to light isotopes of carbon (^{13}C vs. ^{12}C) and nitrogen (^{15}N vs. ^{14}N) are measured. These isotopic ratios are expressed relative to predetermined standard materials, providing natural stable isotopic 'signatures' ($\delta\ ^{13}C$ and $\delta\ ^{15}N$), which can be characterized for any tissues that contain these elements. Stable isotopes are useful as food web tracers as a result of their well-known behavior in ecosystems. $\delta\ ^{13}C$ values are the same between predator and prey, but differ among benthic algae and phytoplankton. Thus, we can estimate whether a consumer is supported by a benthic vs. pelagic food chain. $\delta\ ^{15}N$ signatures increase predictably up the food chain, thereby reflecting a consumer's trophic height or food chain length. The two approaches used in concert provide complementary and useful information about food web structure.

The advantages over traditional dietary-based food web studies are that they reflect time-integrated diets of assimilated, rather than ingested, food. Furthermore, stable isotope techniques can be used to infer historical food web relationships by performing analysis on archived tissue samples. Thus, this technique will allow us to produce a historical reconstruction of the original feeding behavior of native Lahontan cutthroat trout in Tahoe and the subsequent alterations to the system, ending up with a quantitative assessment of the current state of the fishery.

Significance of Research

While there have been many species introductions into Lake Tahoe in the past, some of these adversely effected water quality, biodiversity, and abundance of native fish (Goldman, 1979; Thiede, 1997). Many of these impacts could have been avoided if preliminary research had been conducted to assess the implications of the introductions. The primary goal of this research is to provide resource managers with information that can positively guide Lahontan cutthroat trout restoration efforts into Lake Tahoe. Prior to successful reintroduction efforts it is imperative to understand the original feeding behavior of the cutthroat trout as well as the potential impact the introduction may have on the current fishery. Furthermore, the establishment of a two recently introduced bass species could substantially impact restoration efforts by overlapping with cutthroat trout habitat and removing forage fish resources which are already depressed from pre-introduction times. This project addresses all of these issues and will provide a current assessment of the state of the Lake Tahoe food web for managers to refer to when planning restoration efforts.

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Developing Research

BENTHIC MACROINVERTEBRATE BIODIVERSITY AND COMMUNITY STRUCTURE AS BIOLOGICAL INDICATORS OF WATERSHED RESTORATION PROJECTS

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Background/Hypotheses

Land use impacts may have significant effects on the ecology of the watershed, specifically aquatic insects in streams flowing into Lake Tahoe. It is important to study the potential use of aquatic insects as biological indicators of stream ecosystem health in the Tahoe basin. The goal is to extract biological patterns from macroinvertebrate diversity and abundance and relate these patterns to human induced and natural changes in the watershed (Fore et al. 1996, Barbour et al. 1996). Benthic macroinvertebrates from streams in various stages of restoration will be collected, categorized and quantified. The results will provide necessary data for adaptive management land use decisions and determine the feasibility of using benthic macroinvertebrates as biological indicators in sub-alpine streams. The University of California Tahoe Research Group will integrate this project into ongoing research in the Tahoe basin. Furthermore, the California Tahoe Conservancy is providing funding for the project and will continue monitoring selected streams in the future.

Research on aquatic macroinvertebrates will have several benefits both to research contributions in the field as well as the Lake Tahoe community. An evaluation of the benthic macroinvertebrates will provide information on biodiversity, potential new and unique families and genera, and the trophic dynamics of the benthic macroinvertebrates in the Tahoe basin. Also, the research provides an assessment of the added value of completed restoration activities as exemplified by stream macroinvertebrate fauna. Scientific benefits of the proposed research are the initiation of a stream benthic macroinvertebrate collection for the Tahoe basin that will provide initial baseline data to continue aquatic benthic macroinvertebrate monitoring for streams in the Tahoe basin in the future. In addition, based on the data collected, a Stream Condition Index specific to the Tahoe basin will be attempted. Finally, the project is beneficial to the governmental agencies in evaluating past restoration activities as well as providing direction for future monies spent on restoration in the Tahoe Basin. The research will test the following hypotheses:

1. Successfully restored streams have similar aquatic communities as compared to pristine reference sites;
2. Degraded streams have lower biodiversity and species richness indices as pristine reference sites, and impacted and restored streams.

Aquatic insects have been shown to be sensitive and informative indicators of stream ecosystem health and water quality (Resh et al. 1995). Biological integrity of an aquatic ecosystem is operationally defined as the state of the biotic community in systems with minimal human disturbance (Jackson and Davis 1995). The principal behind bioassessment is to determine the biological integrity of an impacted site by comparing its biotic community to that of a known unimpacted or reference site. Benthic stream insects are becoming a critical component of bioassessment because they are more diverse and ubiquitous and abundant than fish and because these organisms are in contact with both the water and bottom sediment in streams. Macroinvertebrate studies have contributed to an understanding and assessment of stream ecosystem health as related to land-use activities.

Linkage to Restoration

The main purpose of restoration activities is to maintain stream ecological integrity in order to minimize the amount of sediment entering the stream ecosystem and ultimately the lake. The California Tahoe Conservancy had identified the following specific goals of their stream restoration activities including: 1) restore and maintain the natural hydrologic functions of the stream ecosystem with natural flood regimes and groundwater flow; 2) decrease erosion and sedimentation transport by using natural and/or artificial barriers; 3) plant native vegetation along the surrounding riparian corridor; and 4) restore the natural nutrient uptake of the stream waters and stream banks. Benthic macroinvertebrate sampling helps evaluate restoration results. An investigation of benthic macroinvertebrates will be very useful in developing our understanding of the relationship between stream biota and physical changes in stream.

Study Design

Streams in various stages of restoration have been selected and sampling will occur over two seasons - 1999 and 2000. Five streams were chosen in each of the following three categories: 1) reference 2) impacted and not restored, and 3) impacted and restored. The selected streams are as follows: 1) reference - Burton Creek, Eagle Creek, General Creek, Glen Alpine Creek, Meeks Creek; 2) impacted and not restored - Blackwood Creek, Snow Creek, Trout Creek, Upper Truckee River, and Ward Creek; and 3) impacted and restored - Angora Creek, Burke Creek, Cold Creek, Griff Creek, and Lonely Gulch. The reference sites were chosen based on the natural history of the basin as well as conversations with scientists working in the field. Two of the impacted and not restored sites Snow Creek and Trout are scheduled for restoration by the California Tahoe Conservancy during the spring / summer of 2000. These sites will be examined before restoration to assess initial conditions and as restoration proceeds. The remaining three heavily impacted streams, Blackwood Creek, Ward Creek and the Upper Truckee River have been proposed as future restoration sites within the next five years. Consequently, the proposed research will provide initial long-term baseline monitoring conditions that can be compared to any benefits of future restoration activities. The California Tahoe Conservancy has completed restoration work along four of the five impacted and restored streams: Angora Creek (1997), Griff Creek and Lonely Gulch (1994). Other governmental and / or private interests in the basin restored Burton Creek and Burke Creek.

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PATTERNS OF NITROGEN TRANSPORT IN STREAMS OF THE LAKE TAHOE BASIN, CALIFORNIA-NEVADA

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Human intervention in the global nitrogen cycle has increased dramatically in the last half-century. The effects of excess nitrogen from fertilizer and sewage on aquatic ecosystems and groundwater supplies have long been recognized. More recently, nitrogen saturation--an excess of available nitrogen over the biotic and abiotic retention capacity of terrestrial ecosystems-- has led to increased attention to nitrogen cycling and to the linkages between terrestrial and aquatic ecosystems. At Lake Tahoe, the accumulation of nitrogen, over half of it originating in direct atmospheric deposition to the lake, has been sufficient to shift the primary limiting nutrient in the lake from nitrogen to phosphorus. Because of the importance of human-induced changes to the global nitrogen cycle, the results of water quality monitoring at Tahoe are of interest far beyond the boundaries of the Tahoe basin.

The data base of the Lake Tahoe Interagency Monitoring Program (LTIMP) provides a unique opportunity to characterize the spatial and temporal patterns of nitrogen transport in subalpine streams. We hope to answer the following questions: 1) What is the relative importance of nitrate-N, ammonium-N and organic N in stream loads, and how do the concentrations of different forms vary with season and discharge? 2) What are the major sources of the different forms of nitrogen in basin streams? 3) What are the major hydrological and biogeochemical controls on the flux the different forms of nitrogen to the lake? 4) How does the biological availability of particulate and dissolved organic nitrogen relate to its origin? Although the LTIMP data may not provide definitive answers to all of these questions, they do allow us to frame the questions heuristically. As a first step in this analysis, we calculated discharge-weighted mean concentrations for nitrate-nitrogen, ammonium nitrogen, and dissolved and particulate organic nitrogen for 10 watersheds. We also calculated total loads of nitrate-N, ammonium-N and organic N (dissolved plus particulate), for the 10 LTIMP watersheds, over the period 1989-1998.

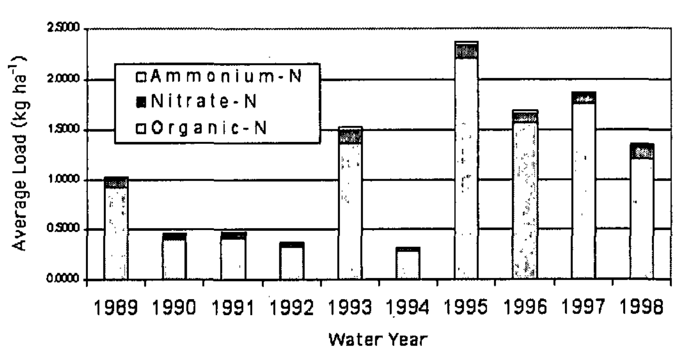
The figures below show the total nitrogen loads, averaged over the ten years for each watershed, and averaged over area for each year. Both the concentration and total loads of nitrogen in basin streams are dominated by organic nitrogen. Nitrate-nitrogen accounts for about 7 percent of the nitrogen load and ammonium-nitrogen for only about 1.5 percent. On average, about 55 percent of the organic nitrogen is dissolved, although this fraction varies widely among streams. Dissolved organic nitrogen (DON), like nitrate, is highest at high discharge early in the runoff season. It typically drops during late snowmelt, but increases again during the summer low-flow period, probably due to instream biological activity. Intense summer rainstorms, especially on the east side of the basin, are responsible for the highest peaks in organic nitrogen.

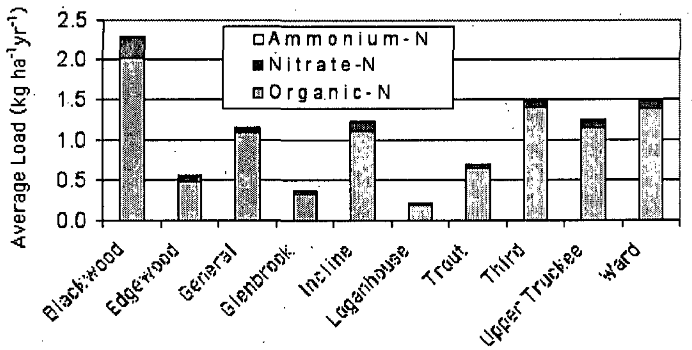
The dominance of organic nitrogen in basin streams contrasts sharply with streams in the eastern U.S., where nitrate is the most important form in transport. In spite of the basin's air quality problems, it has not yet approached the levels of nitrogen deposition that are characteristic of much of eastern North America.

The biological availability of the organic nitrogen in the streams and lake is an important open question. Probably the availability changes with season, hydrologic conditions, and the flow-paths of water through the forest floor and soil.

At the basin and decadal scales, the temporal and spatial variation in total nitrogen load is explained largely by variation in annual runoff. The relationship between annual runoff and total annual nitrogen load is good enough that annual runoff alone could now be used to estimate total annual nitrogen load to the lake from the 10 LTIMP streams.

Future work on nitrogen in Tahoe basin streams might focus on 1) relationships between watershed characteristics (soils, vegetation, hydrogeology and land use) and nitrogen yield; 2) concentrations of particulate organic nitrogen, dissolved organic nitrogen, and dissolved inorganic nitrogen in relation to hydrologic flowpaths and runoff events; 3) the sources and biological availability of dissolved organic nitrogen in streamwater; 4) methodologies for calculating total load; and 5) the contribution of urban runoff to the nitrogen load of the lake.





Average Load (kg ha^{-1}yr^{-1})
2.5
2.0
1.5
1.0
0.5
0.0
Ammonium-N
Nitrate-N
Organic-N
Blackwood
Edgewood
General
Glenbrook
Incline
Logarhouse
Trout
Third
Upper Truckee
Ward

A LONG-TERM DOWNWARD TREND

IN BLACKWOOD CREEK NITRATE-NITROGEN CONCENTRATIONS

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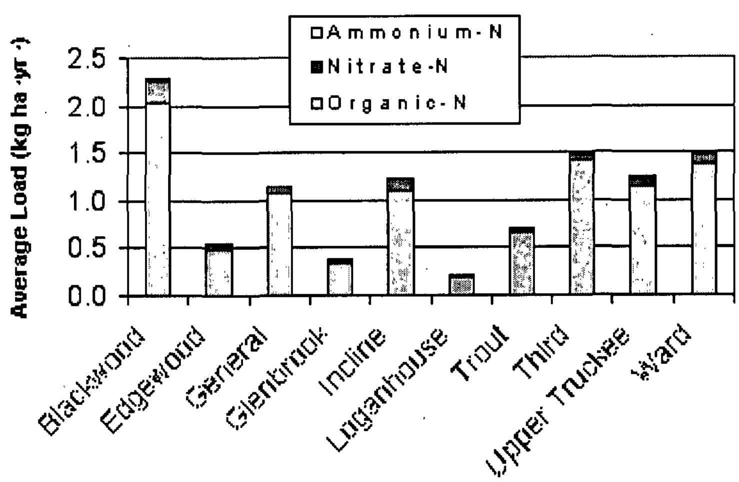
Introduction

Blackwood Creek, a 2900 ha watershed on the west side of the Tahoe Basin, has the highest yield average annual yield of nitrate-nitrogen and organic nitrogen of any gaged stream in the Tahoe basin (Figure 1). Investigators have known of the high nitrate yield of the watershed for over 20 years, and have usually attributed the high yield to a history of land disturbance (Leonard, et al. 1979). In 1986, investigators of the Tahoe Research Group noted a downward trend in the nitrate-nitrogen concentration of Blackwood Creek from 1976 to 1985, and attributed this to recovery of the watershed from the heavy logging, grazing and channel disturbance of the 1960s (Byron and Goldman, 1986). The availability of additional data now allows us to test the apparent time trend more rigorously.



Figure

1. Mean annual nitrogen yields for 10 Tahoe basin streams, 1989-98

Good records of land use in Blackwood Creek do not seem to exist. The basin was logged during the mid to late 1800s. Second-growth and residual old-growth stands were tractor logged during the 1960s, and meadows were heavily grazed (Lowry, 1994). The channel of Blackwood Creek was diverted, and gravel was mined from the alluvium of the old channel. In 1987 and 1988 the Forest Service restored Blackwood Creek to its original channel, removed woody debris jams and beaver dams that were blocking fish passage, and restored riparian and wetland vegetation in the gravel mine area. Subsequent monitoring of the effects of the restoration on water quality showed a reduction in suspended sediment but no measurable effect on nitrate-nitrogen concentrations (Lowry, 1994).

Tests for a Time Trend

In order to test for a long-term time trend in the nitrate signal of the watershed, we regressed all of the available nitrate-N data for Blackwood Creek against time. We also used a sliding regression to compare same-day samples from Ward and Blackwood Creeks, from WY 1976-78 and 80-96 (1100 pairs). Ward Valley is adjacent to Blackwood canyon, has similar geology and hydrologic conditions, but a more benign land use history. The sliding regression used a 4-year window, and moved the window 1/12 of a year for each recalculation. The significance of the apparent time trend was tested with a permutation analysis (Manly, 1997). In this Monte Carlo technique, the water years are reordered at random (in this case 500 times), and the sliding regression is run again. By using pairs of daily samples from Ward and Blackwood Creeks, we can rule out external causes of a downward trend, since changes in the analytical method for nitrate, or a time trend in atmospheric deposition could be expected to affect both watersheds.

Results

Figure 2 shows all of nitrate data for Blackwood Creek, 1974-99, along with the trend line. The regression of concentration against time is highly significant, and slope of this line is significantly different from 0 ($P<10^{-24}$).

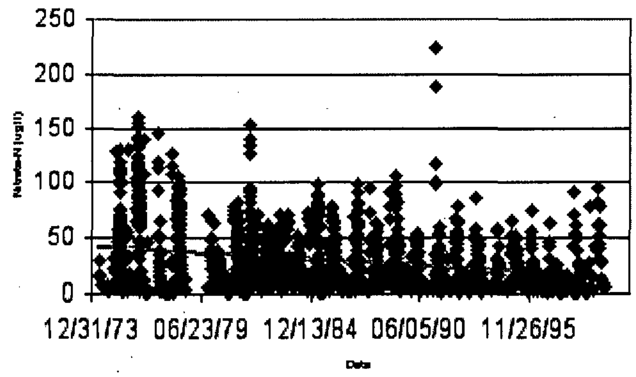


Figure 2. Time for nitrate-N concentrations in Blackwood Creek, 1974-98.

The regression of daily values for Blackwood against Ward showed that from 1976 to 1996, the nitrate-nitrogen concentration in Blackwood Creek has decreased relative to that of Ward Creek. The permutation test for significance, in which the water years were re-ordered at random 500 times, and the regression re-run, showed that the time trend is real ($p<0.002$). The most likely explanation for the time trend is that the soil-vegetation system of Blackwood Creek basin has been recovering from past disturbance over the last 20 years, and is becoming more efficient at retaining nitrate-nitrogen.

Acknowledgments

Peter Baker assisted with the statistical analysis. Data are from the Lake Tahoe Interagency Monitoring Program, made available by Dr. Charles Goldman. An earlier version of this was included in a poster titled "Soil type, land disturbance and streamwater nitrate in three watersheds of the Lake Tahoe basin", presented at the 9th North American Forest Soils Conference, Granlibaaken, 1998.

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Contribution of Basin Watersheds and Atmospheric Deposition to Eutrophication at Lake Tahoe, CA-NV, USA

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Overview

Known for its beauty, remarkable transparency and cobalt blue color, Lake Tahoe (CA-NV) is a natural jewel in the Sierra Nevada mountains. Its serves as the focus for millions of visitors annually and is internationally recognized. However, human development over the last five decades has been damaging. The lake has responded to increased nutrient loading from streams, groundwater and urban runoff as well as atmospheric sources, with steadily increasing algal growth and a progressive reduction of clarity. The lake has lost over 10 meters (>30 feet) of transparency during the last 30 years and algal primary productivity has increased by 5-6% annually over the same period. If allowed to continue unabated, the lake will lose its remarkable clarity and likely change color in only 30 more years.

Environmental Setting

Lake Tahoe lies in the crest of the Sierra Nevada at an elevation of 1,898 m within both California and Nevada. The drainage area is 812 km2 with a lake surface of 501 km2. The lake is located in a montane-subalpine watershed dominated by coniferous vegetation and nutrient-poor soils. It is the world's eleventh deepest lake at 505 m with a mean depth of 313 m. Its volume is 156 km3, with a hydraulic residence time of about 650-700 years, and is ice-free.

Lake Tahoe was once classified as ultra-oligotrophic (i.e. low nutrient content, low plant productivity and high transparency)(Goldman, 1981). However, because of the ongoing decline in clarity and rise in algal growth rate, its level of fertility has been increasing. Extensive research on the spatial distribution of phytoplankton algae indicates a marked correspondence between growth rate and urbanization. Attached algae also demonstrate this pattern.

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 effect - this is no longer the case. We now know that once nutrients enter the lake they remain in the water and are recycled (Jassby et al., 1995). Research has also shown a shift from nitrogen to phosphorus as the primary limiting nutrient (Goldman, 1993), a change attributed to direct atmospheric deposition of nitrogen to the lake. Since phosphorus is typically

transported along with sediment, our findings underscore the importance of sediment control, erosion mitigation, acquisition of sensitive lands, and other means of restoration.

Lake Tahoe Nutrient Budgets

For decades, planning, regulatory and implementation actions in the Tahoe basin have focused on controlling nutrient and sediment inputs to the lake. Examples include, but are not limited to, acquisition of environmentally sensitive lands, building restrictions, BMP retrofitting, erosion control, installation of BMPs for treatment of surface runoff, permits and education. With large sums of money now being spent on environmental restoration, it is more important than ever an accurate nutrient and sediment budgets for the lake.

Five major categories of nutrient loading to Lake Tahoe have been identified (1) direct atmospheric deposition and precipitation, (2) stream discharge, (3) overland runoff directly to lake, (4) groundwater and (5) shoreline erosion. The major losses include settling of material from the water column to the bottom and discharge to the Truckee River, the sole tributary outflow.

Atmospheric deposition

Jassby et al. (1994) suggested that atmospheric deposition provides most of the dissolved inorganic nitrogen and over half of the total nitrogen to the loading budget of Lake Tahoe, and also contributes significant amounts of soluble reactive-P and total-P.

Direct N-loading to the lake surface was recently estimated at 234 MT yr^{-1} and P contribution at 12.4 MT yr^{-1} (1 MT = 1,000 kg or 2,205 pounds). This accounts for 56% and 27% of the annual TN and TP budgets, respectively. We hypothesize that P present in precipitation and dry fallout results from wood smoke, road dust and aeolian (wind) transport from disturbed land. Sources of N come from both within the Tahoe basin and outside the basin, and may include automobile emissions, and agrochemical residues.

Stream Loading

Using data of the Lake Tahoe Interagency Monitoring Program from the early 1980s to the early 1990s the Tahoe Research Group has calculated stream loads for N and P as part of two separate studies. The results for annual N-loading were 81.1 MT yr^{-1} and 55.2 MT yr^{-1} for the beginning and end of this period, respectively. Comparable loading values for total-P were 12.5 MT yr^{-1}, and 11.2 MT yr^{-1}(Marjanovic 1989; Jassby et al. 1994). Differences from period-to-period reflect the variation in precipitation and runoff. Contributions for N and P in our budget were taken as the mean, or 68.2 MT yr^{-1} and 11.9 MT yr^{-1} , respectively. Thodal (1997) and Dugan and McGauhey (1974) also estimated streamflow nutrient loads; averaging their estimates with the more recent estimates produces loading estimates of 81.6 MT yr^{-1} and 13.3 MT yr^{-1} for total-N and total-P, respectively. These account for 20% and 29% of the N and P budgets. Recent improvements in the method used to calculate total nutrient loads may decrease the estimated stream contributions, but will likely not much change their estimated relative importance in the lake's nutrient budgets (Coats and Goldman, 2000).

Direct Runoff

The Tahoe basin has 52 intervening zones which drain directly into the lake without first entering the streams. These intervening zones are generally found between the individual watersheds and as such are distributed around the entire lake. Based on a study of urban runoff at South Shore in 1983-84 by the Lahontan Regional Water Quality Control Board and a series of four runoff studies by the Tahoe Research Group between 1993 and 1998, we estimated the loading from direct non-stream runoff at 41.8 MT yr^{-1} for total N (10% of the total-N budget) and P-loading 15.5 MT yr^{-1} for total P (34% of the total-P budget). The observation regarding the high contribution of P-loading from direct runoff is particularly important since a significant portion of the urbanization at Tahoe is found in the intervening zones. It provides project planners with the understanding that control and treatment of urban/direct runoff to the lake is critical and should be a high priority.

Groundwater

The most comprehensive, basin-wide groundwater study to date is that of Thodal (1997). He calculated "rounded estimates" of 60 MT yr^{-1} for N-loading and a 4 MT yr^{-1} for P-loading. This accounted for 14% of the TN budget and 9% of the TP budget.

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 when the combination of high lake levels and strong and sustained winds eroded areas of the western shoreline by many feet. A rough estimate based on rates of shoreline erosion and average nutrient concentrations in soils around the lake yields estimates of 0.5-1.0 MT yr-1 total N and 0.3-0.6 MT yr-1 for total P. Both values are less than the errors in the other estimates; however, more quantitative estimates of erosion loss are needed.

Below, we summarizes these loading estimates expressed as metric tons per year.

	Total N	Total P	Dissolved P
Atmospheric deposition	233.9 (56%)	12.4 (27%)	5.6 (33%)
Stream loading	81.6 (20%)	13.3 (29%)	2.4 (14%)
Direct runoff	41.8 (10%)	15.5 (34%)	5.0 (29%)
Groundwater	60 (14%)	4 (9%)	4 (24%)
Shoreline erosion	0.75 (<1%)	0.45 (1%)	No Data
Total	**418.1**	**45.7**	**17.0**

The budget clearly suggests the importance of direct runoff as an important P source from urban areas and highlights the need for additional study in this area. However, phosphorus reduction strategies at Lake Tahoe will have to address multiple sources including direct runoff, atmospheric deposition and stream loading. At the same time, the contribution of atmospheric deposition to the N budget clearly dominates other sources. Using the estimated loading of dissolved-P as a first approximation of biologically available-P (BAP), this budget further shows that BAP is on the order of 35-40 of total-P. This is not uncommon; however, the 17 MT value may underestimate true BAP. Research to investigate this further has been proposed. Looking at dissolved-P alone, the relative importance of the groundwater contribution increases.

Heyvaert (unpub. data) has found that nutrient sedimentation losses to the bottom of Lake Tahoe are 401.7 MT yr^{-1} for total-N and 52.8 MT yr^{-1} for total P. These agree remarkably well with the independent loading estimates given above. This close agreement give us increased confidence that the loading rates are representative.

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Modeling flow, sediment, and nutrient transport from the Lake Tahoe watersheds

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Introduction

Over the past decades, the water quality of Lake Tahoe has deteriorated quite rapidly. Much of it was due to the algal growth within the lake, which in turn affected the lake clarity. It is now found that the lake has shifted its condition from the nitrogen (N)-limited to the phosphorous (P)-limited. For this reason, the control of the phosphorous loading into the lake through various routes became a very important issue. In the recent study on the nutrient budget of the Lake Tahoe by the Tahoe Research Group at UC Davis, it was found that the direct runoff from the intervening zones and the loading from the streams are the major contributors of the phosphorous input to the Lake. Hence, the modeling of sediment/nutrient transport from the tributary watersheds of the Lake becomes an important starting block for the comprehensive lake clarity model as it provides the information on the required phosphorous loading.

Methodology

In order to model the sediment/nutrient transport from a watershed, a watershed hydrology model becomes a prerequisite since the water flow is the mechanism that drives the transport of sediment/nutrient. For the hydrology component of the model, we have taken the physically-based approach, which employs the conservation equations for water flow. With its physically sound nature, the model has advantages over conceptual models in application to an ungaged watershed and in being capable of testing alternative scenarios of changes in the environment and their impact on the hydrology of the watershed. For similar reasons, transport component of the model is also based on the physically-based transport equation which includes advection and diffusion terms.

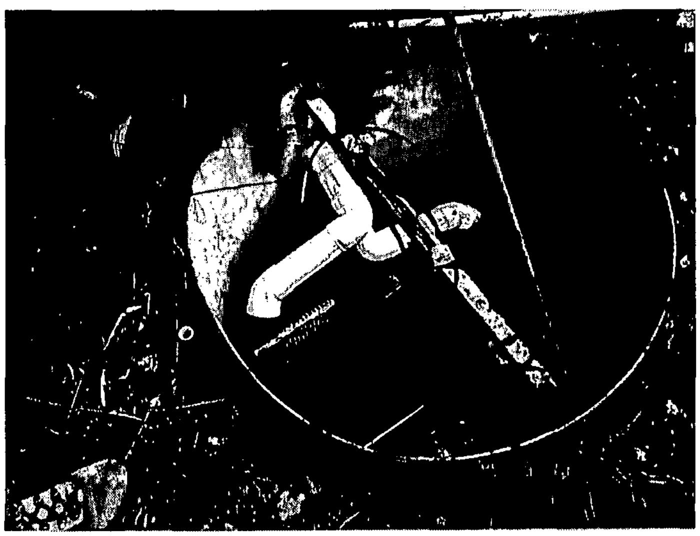
Hydrology Model

The watershed hydrology model is made up of the following components: (a) an overland flow model which describes both the rill flow and the interrill-area sheet flow; (b) a land surface hydrology model which describes the interception, evapotranspiration and soil unsaturated flow processes; (c) a snowmelt model; (d) a subsurface stormflow model which describes the fast saturated flow that forms above an impeding soil layer below the plant root zone; (e) a deep unconfined groundwater aquifer flow model; and (f) a stream network flow routing model based upon diffusion wave approximation. All of these components, except for the streamflow routing and the groundwater component, are based upon areally-averaged conservation equations.

Based upon the calibration of model parameters, the validation of the proposed hydrology model has been performed for the Ward Creek watershed where the sediment and associated phosphorous loading was identified to be significant. Three consecutive rainfall events during the month of September, 1998 were used to verify the performance of the model. It is important to note that our calibration is different from the traditional one used with many conceptual models in that all parameters are estimated physically using the Geographic Information System of the watershed, based upon available base maps such as digital elevation model, soils map, and vegetation map, rather than through model fitting. The runoff simulation results from the model were compared to their observed counterpart and showed good resemblance, thus verifying the performance of the model.

In addition to the validation of the model, an interesting application of the model to the Ward Creek watershed has been made to investigate the impact of different fire scenarios. The main objective of this study was to test the model's utility as an environmental risk-assessment tool. The capability to assess the impact of fire on the hydrology of the watershed is a valuable asset since it can provide necessary hydrologic input to further analyze environmental risks involved with fire, such as erosion, nutrient transport, and landslide. Three different fire scenarios were simulated for the same period used in validating the model, and they corresponded to a 20-year return period fire, a 40-year return period fire, and wildfire. Although the watershed model simulations of hydrologic runoff processes at Ward Creek watershed have not produced significant difference between the unburned conditions and fire conditions, it is important to note that these simulations covered only a short period of a week in the beginning of September 1998. In fact this was in good agreement with the experiments performed in Lake Tahoe Basin by USDA Forest Service where they found no visible change in the hydrological processes after a prescribed fire over a short-term period. However, the clearing of vegetation after fire can be a major source of environmental risks such as erosion and landslide from a long-term perspective.

Along with the modeling of the watershed processes, there have been efforts to set up an experimental site to provide valuable data for the validation of the model at a field scale. A site in the upper reaches of the Ward Valley was selected for the study of subsurface and overland flow contributions to a stream. The source area is approximately 4000 square feet with a mild, concave, downward slope to the stream bank. In winter and spring, this area is often covered with as much as 15 feet of snow. The area is clear of snow by early May to late June. Upon review of the data from the spring melt of 1999, it was concluded that saturated overland flow was occurring at the bottom of the snowpack during the peak melt periods. Overland flow, even as a basal flow within the snowpack, is a potentially important sediment and phophate transport mechanism. In fact, at the time that overland flow was occurring, water quality samples of the adjacent stream showed that suspended sediment concentrations were much higher than average.



Transport Model

Erosion/sediment and nutrient transport model is being built on the foundation of a watershed hydrology model, which has been developed recently. This will finalize the development of a source loading model for sediment and nutrients. The erosion and sediment transport model will mainly consist of two distinct processes: upland (hillslope) and channel erosion/sediment transport. Both processes will be modeled by the conservation of mass equation for sediment, which has erosion and lateral sediment influx terms. The erosion term can be further divided into rain splash erosion and hydraulic erosion due to the shear force of the surface runoff, of which the former is only considered for the upland processes. Lateral sediment loading becomes important for the channel process as it receives contribution from hillslopes. From the water quality standpoint, the portion of nutrient that is transported in a form adsorbed to the sediment will be accounted for in this module. The nutrient transport in a soluble phase will be modeled in a similar fashion to the erosion and sediment transport process using the corresponding advection-diffusion equation. In all these transport models hydrologic variables such as flow depth and velocity are required, as they are the driving mechanisms for the pollution transport, and will be provided through the hydrology model. Since all the components of the watershed model are based on relevant physical principles, the model will have the capability to perform what-if scenarios on the impact of natural/human disturbances such as road network, logging, fire, and urbanization. Once the calibration and validation are performed using the historical flow and water quality data, proposed non-point source-loading model for sediment and nutrient will provide necessary inputs to the lake clarity model as a boundary condition.

Summary

As the first building block within the framework of comprehensive lake clarity model, the watershed sediment/nutrient transport model is closely tied to the lake hydrodynamic and water quality model and statistical lake response model that relate the lake variables to lake clarity represented by Secchi depth. When complete, the comprehensive watershed model can be used as a useful tool to quantify the impact of alternative land management scenarios. One of the benefits from this feature of the model would be the capability to prioritize the ongoing restoration efforts over Tahoe basin based upon the efficiency in reducing the nutrient loading to the Lake Tahoe, especially phosphorous loading. This would allow decision-makers to focus on the highly efficient loading spots within the basin, providing a most economical solution with limited resources available. The model can also be used in a backward manner to actively seek for restoration practice and its location in order to meet the lake clarity goal, set by the agencies. That is, based upon the goal set for the lake water clarity, the lake model can provide the amount of reduction in phosphorous loading required to achieve that goal, and subsequently the source-loading model can be utilized to answer where and which method is going to meet that requirement. Overall, the proposed source-loading model will provide an important solution to the complex ecological puzzle of Lake Tahoe.

Sediment Sources in Ward Valley

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Introduction

Long term monitoring of suspended sediments and nutrients in streamwater entering Lake Tahoe has focused attention on four watersheds: Incline Creek and Third Creek in North Tahoe, Ward and Blackwood on the West Shore and the Upper Truckee River draining South Lake Tahoe. Ward Creek was chosen for further study because of existing monitoring information and previous research on the watershed. It received a 303(d) listing by the California Regional Water Quality Board as an impaired water body because its contribution of sediment and nutrients to the Lake was above regulatory thresholds. The purpose of this study is to identify major watershed sediment sources for restoration efforts and to gain insight into the temporal and spatial dynamics of sediment loading in subalpine watersheds. The Lake Tahoe Interagency Monitoring Program has maintained three sampling stations in Ward Creek. In 1999 we installed four continuously recording turbidity meters. One was installed at the mouth LTIMP station, one at the mid station, and one on each of the main forks, North and South. Hand sampling was conducted on a weekly basis during the snowmelt in order to generate a correlation between turbidity and sediment loading and to sample smaller tributaries draining the Scott Peak and Paige Meadows subcatchments.

We found an excellent correlation between turbidity and suspended sediment (Figure 1. R^2=0.93). We multiplied suspended sediment concentrations determined from turbidity calculations by the discharge information provided by the LTIMP sampling stations and hand measurements. This calculation allowed us to generate sediment loading for subcatchments within Ward Creek for the 1999 snowmelt. The results from the turbidity meters are shown in Figure 2. The South Fork generated 22% of the total sediment load. The North Fork generated 6%. The reach between the confluence of the South and North Forks and the mid station - upper main stem- generated 64% of the sediment load. The reach between the mid station and the river mouth - the lower main stem- generated 8% of the sediment load. The high sediment load from the South Fork is from the badlands region- approximately 30 hectares of steep, unvegetated gullies and ravines at the top of the watershed. The 22% figure represents an underestimate of the contribution of the South Fork on a yearly basis. Summer and fall thunderstorms have been observed to coat the channel of the main stem with fine sediment washed from the badlands region. In the spring when the river levels rise, the material is moved out to the Lake. Thus a portion of the 64% coming from the upper main stem may be temporarily stored South Fork sediment. The other portion coming from the upper main stem comes from channel bank erosion. During high flow events the river meanders and cuts through the stored sediment deposits. The lower main stem is steeper and more of a canyon shape. The steep gradient means that even at low flow sediment is moved out into the lake and not stored. Hand sampling results supported the turbidity information. The Paige Meadow and Scott Peak tributaries did not supply significant sediment loading to the main channel. Paige Meadow and would be expected to have low sediment output because wetlands are excellent sediment traps. The Scott Peak subwatershed is largely forested. Undisturbed forestlands generally have low sediment output.

Information from this research will be useful for watershed restoration activities of the USFS and the Total Maximum Daily Load process underway by the Regional Water Quality Control Board. The research is informative for the sediment transport model being designed by Professor Kavvas of UC Davis Civil and Environmental Engineering.

WATERSHED EFFECTS OF PRESCRIBED FIRE IN MIXED CONIFER ECOSYSTEMS: A CASE STUDY FROM THE LAKE TAHOE BASIN

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This study examined the effects of the prescribed burn program carried out by the California State Parks System annually for the last 8 years on General Creek's watershed in Sugar Pine Point State Park. The objective was to assess the possibility of reclaiming forest health without harming the Lake Tahoe Basin's aquatic health. It has been confirmed that the forest in Sugar Pine Point State Park is becoming dominated by white fir with less spacing, as demonstrated by consistently high recruitment and reduced distances between individuals across all forested burn units for trees <150 years old (post-Comstock). The large natural variation in precipitation and discharge during the past 8 years has made it difficult to separate out changing watershed effects of prescribed burn practices versus interannual changes in climatic effects on watershed parameters. This is exemplified by the noticeable increase in total suspended sediment in General Creek when compared to Meeks Creek. For water year 1999, the loadings of all nutrients examined (total phosphorus, soluble reactive phosphorus, ammonia, nitrate) tended to follow the trend in the hydrograph while the concentrations were more variable over time.

There were no statistically significant differences between loads for all constituents across downstream sites for the comparison of General Creek (treatment stream) and Meeks Creek (reference stream) during water year 1999. Though there is greater total phosphorus concentration downstream of the prescribed burns, there is no increased total phosphorus load downstream of these treatments. The results of soluble reactive phosphorus analyses are equivocal when we consider the effects of prescribed burning on aquatic health for 1999. Both soluble reactive phosphorus concentration and loading were greater in the treatment watershed's downstream site when compared to its upstream site. Though there were elevated values of soluble reactive phosphorus concentration when evaluating the treatment stream with the reference stream, these discrepancies did not hold for loading. Nitrate and ammonia demonstrated a locally variable pattern that was supported by only one statistically significant comparison, which showed higher nitrate concentrations upstream of the prescribed burn units. Future research should attempt to assess the proportion of prescribed fire's overall contribution to in-basin loading.

Tahoe's Old-growth Forests: Islands in a Sea of Recovery

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The Tahoe Regional Planning Agency's "Forest Consensus Group" has proposed that 80% of the basin's forests be managed so that they will achieve old-growth status in the future. In order to imagine that future landscape more clearly, and to predict its impact on water and air quality, we need to quantitatively describe existing old-growth forests in the basin.

Such forests are rare. During extensive logging in the late 1800s, almost 60% of the 38,340 hectares of forest were clearcut or partially harvested (the percent of trees taken ranging from 10 to 100%). At low elevations and on slopes easy to access, the harvest was much greater than 60%; at high elevations and on steep slopes, the harvest was less than 60%. The 40% that was unentered for harvest did not remain as one or even several large contiguous patches, but rather as many quite small and scattered stands. The old-growth forest was not only rare, it was fragmented.

We recently surveyed much of the modern forest's extent and were able to locate fewer than 40 old-growth stands. They averaged 25 ha in size, were seldom near one another, and laid scattered throughout the basin. The combined area of the old-growth stands comprise only 3% of forested land in the basin. This value is much lower than the 13% old-growth area for all the national forests in California and the 55% old-growth area for all the national parks in the Sierra Nevada.

The patches of old-growth forest are dominated by relatively tall, large diameter trees. Just under 20% of all the overstory trees (trees older than 200 years) in an average stand have a diameter breast height of 76 cm or greater--a diameter large enough to support such endangered old-growth animals as the California spotted owl. Unlike nearby, younger second-growth forest, old-growth stands are relatively open and rich in pines (the ratio of pine:fir is 1:3). Second-growth forests are several times denser in understory trees and they are less rich in pines (pine:fir = 1:6). Old-growth forests also seem healthier: the percent of trees exhibiting disease is 41% less, and the percent of dead trees is 24% less, than second growth forests. Evidently, the low density of trees in old-growth forests allowed these stands to pass through the drought of 1987-92 with fewer deaths than the surrounding matrix of second-growth forest.

We believe that it will be possible to move second-growth forest towards old-growth status in the least amount of time by practicing some active management. That management would include the re-introduction of periodic surface fires into the forest coupled with the harvest of many young trees and some old trees. In the past, prior to the arrival of Euro-Americans, surface fires were common. They were sometimes started by Native Americans and more often by lightning strikes. Normally the fire crept slowly along the ground, consuming only litter, herbs, shrubs, and small trees. Some mature trees, weakened by other stresses, were killed by a surface fire. Where brush or litter accumulated next to a tree trunk, the heat of the fire was great enough to kill a portion of the trunk but not the entire tree. The result was a scar in the wood and a place where subsequent fires were likely to scar the tree again. By examining cores of wood taken from injured trees and counting the scars, fire ecologists have estimated that conifer forests like those in the Tahoe basin experienced a surface fire every 20-30 years, on average.

Surface fires have been suppressed by law for most of the nineteenth century. We now realize that fire suppression was a mistake and that active management should now, somehow, imitate their effect. Purposely set fires (called prescribed fires or burns) can be set on calm days when the water content of the litter is high enough to slow the spread of the fire. Such a fire will not be hot enough to kill enough trees, so there will be a need to additionally thin the forest manually. The result, over time, will be an open forest with a more equal balance of pine and fir and a lower incidence of disease and mortality.

Of course, another result of prescribed fire is the generation of smoke and the possibility that nutrients carried in the smoke will be deposited in Lake Tahoe and negatively affect water quality. Experimental burns near the lake's shore, coupled with a model of air movement, suggest that 12 hectares per day could be burned over a continuous period of 100 summer days without exceeding air quality standards for particulates and other pollutants. In the course of 30 years, the entire forested area would have been burned, creating a 30 year fire return interval.

Approximately 1,200 hectares a year will have to be burned to create a 30-year cycle. (If the present policy of fire suppression and almost no prescribed fire were to be continued, the fire return period will be several hundreds of years!) It may be wise to increase the area burned by prescribed fire gradually over time, rather than instituting it basin-wide. Another reason for phasing in the management is that budgets change slowly and the increased amount of money required for burning/thinning 1000 hectares a year is not likely to be granted by state and federal legislators in the course of a few years. How, then, to begin?

The ideal places to begin this management would be in the neighborhoods immediately adjacent to patches of old-growth forest. The old-growth stands are often far removed from roads and buildings, so the safety factor is high (occasionally, prescribed fires do burn hotter and/or do escape beyond their intended limits). We are surveying these neighborhoods now, to determine which has the most continuous forest cover, the easiest access, and the topography conducive to containing prescribed burns. As experience and confidence are gained from successful burns there, the management policy can be expanded to more distant forests and to greater combined areas.

Traits for old-growth stands in the Tahoe basin

tree cover 45%

tree density 378 per hectare

sapling density 600 per hectare

tree basal area 45 square meters per hectare

shrub cover 20%

herb cover less than 1%

litter cover 75%

litter depth 5 centimeters

coarse woody debris 58 metric tons per hectares

Causes and Patterns of Tree Mortality

in Lake Tahoe Basin Forests

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INTRODUCTION

As in many areas of the western U.S., periodic fire is considered to be a defining influence on ecosystem function and health of Lake Tahoe coniferous forests, altering fundamental plant, soil and microclimate conditions. Historically, frequent low-intensity fire has been the main disturbance dynamic driving ecosystem structure, function and composition. Within the last century, however, fire suppression and logging (both clearcutting and selective harvests) have significantly altered stand conditions in the Lake Tahoe Basin by increasing stem densities of shade-tolerant species, soil litter depth and understory shading. Both understory and overstory tree densities have increased dramatically throughout basin forests; in particular, there has been a doubling in the importance of white fir and incense cedar and a decline in the importance of Jeffrey pine and sugar pine by 50 % (See M. G. Barbour report). Sites that have been previously logged currently exhibit the highest stem densities for both overstory and understory trees.

In association with a recent drought, highly visible levels of tree mortality in the Lake Tahoe Basin began in the mid-1980s. The condition of Lake Tahoe forests has become an important concern for residents and forest managers of the basin. The presence of increased fuel loads, due to years of fire suppression and the recent tree mortality event, and current high densities of living trees has led to fears of a catastrophic fire. Such a fire can threaten human life and property as well as potentially upset historical ecological processes. When such a fire does occur it most likely will be a crown fire that will cause significant tree mortality.

Current Distribution and Extent of Mortality

Based on our 1997 and 1998 ground surveys of 31 stands in the basin, overall cumulative tree mortality in the lower montane forests currently ranges from 9 % to 33 % in 31 sampled stands with mean mortality of 25 % for 14 previously logged stands and 21 % for 17 old growth stands that have never been logged. The majority of the standing dead trees in the Basin have died during the most recent drought (1987-1992), although a number of trees that had died prior to this drought were still found on the sites. Mortality was most common in the 20-50 cm dbh size class. This was also the most common size class at most sites and overall mortality was fairly evenly distributed throughout different size classes. White fir makes up the largest percentage (78 % in logged stands, 62 % in old growth stands) of dead stems in the lower montane forests of the Basin. There is also a positive correlation between tree density and mortality; i.e., the more trees on a site the more likely that there will be a significant mortality event (Fig. 1).

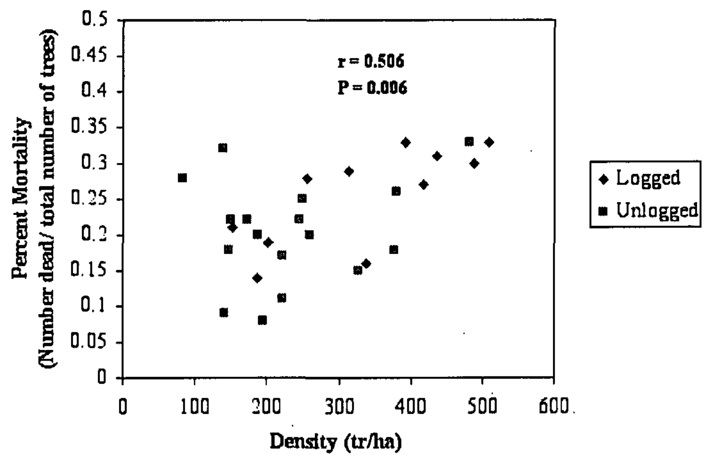

Fig. 1. Relationship between tree density and mortality in the Lake Tahoe Basin between the years of 1985 and 1998.

Causes of Mortality

It has become apparent that in fire-dependent ecosystems, the absence of fire will lead to pests (often in conjunction with drought) and/or mechanical thinning becoming the primary drivers of both mortality and recruitment. Epidemic levels of bark beetles are clearly the most important cause of tree death in the past ten years in the Lake Tahoe Basin. A number of reports show increased mortality of Jeffrey pine due to the Jeffrey Pine beetle (*Dendroctonus jeffreyi*) and white fir due to the fir engraver beetle (*Scolytus ventralis*) during the drought years of 1987-1993. Bark beetles are known to build to epidemic levels by attacking trees under stress due to strong competition for available resources. Such conditions were readily available in the Lake Tahoe Basin during the drought. In addition, a number of pathogens (e.g., root disease and dwarf mistletoe) also play a role in tree mortality in the basin with diseased trees often serving as susceptible hosts for resident populations of bark beetles during inter-drought periods.

For each of the major conifer species, overall pathogen and insect incidence is generally lower on unlogged, old-growth sites as compared to stands that have been previously logged. On logged sites, as a whole, 39 % and 49 % of all Jeffrey pine and white fir stems, respectively, were identified with some pest species. Old growth sites, as a whole, had pest incidence of 23 % and 34 % on Jeffrey pine and white fir. However, there was wide variation in pest incidence from site to site and between the different pest species and these overall differences between seral and late-seral/old growth stands were not statistically significant.

How Typical Are These Mortality And Pest Patterns?

There are very few records of mortality patterns in Lake Tahoe Basin forests prior to the arrival of Euroamericans. We can make a comparison, however, of Lake Tahoe Basin forests with the Sierra San Pedro Martir (SSPM) in Baja, Mexico. The SSPM forests are very similar to those of the Lake Tahoe Basin in terms of overstory tree composition, rainfall, soils, and other ecological parameters. In contrast to the Lake Tahoe Basin, forests of the SSPM have never been logged and still have the historic fire regime intact. Because of this stem densities are much lower in SSPM forests than in Lake Tahoe forests. For trees over 20 cm diameter, densities are 536, 324, and 134 trees/hectare for logged Tahoe sites, unlogged Tahoe sites and the SSPM, respectively. Our studies also indicate that overall tree mortality is significantly lower in SSPM forests than in the Lake Tahoe Basin forests. Estimates of cumulative mortality range from 4 % to 15 % of all trees on the SSPM sites. SSPM forests appear to have escaped the most recent drought without extensive bark beetle outbreaks and, therefore, much lower mortality than was reported for the forests of California (Fig. 2). In addition, mortality on SSPM sites appears to be concentrated in the larger size classes; over 90 % of the dead trees are larger than 50 cm diameter. This contrasts with the data presented here for old growth forests in the Lake Tahoe Basin in which approximately 60% of the mortality was in the 20 to 50 cm diameter size class. This suggests that most stand thinning in SSPM forests is due to fire at the seedling stage and that mortality is largely confined to older trees at SSPM rather intermediate class trees. In contrast, stand thinning in the Lake Tahoe Basin is taking place at a much later point in time in stand development (i.e., when trees are >20 cm diameter). Insects and diseases have apparently replaced fire as the main stand thinning agent in the Tahoe Basin.

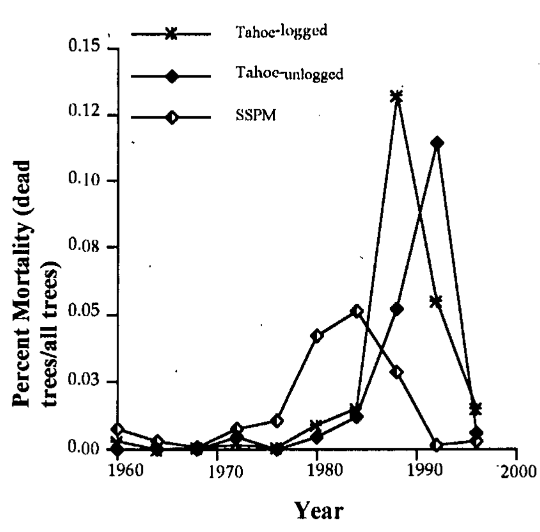

Fig. 2. Mortality curves for mixed-conifer species in the Lake Tahoe Basin and the SSPM.

Possible Forest Health Treatments

A number of proposals have been put forth as ways to improve forest health in the Lake Tahoe Basin. Restoration of basin forests could potentially focus on both stand thinning and prescribed fire. In theory, restoring forests to their natural densities should mitigate most serious pest outbreaks (e.g., reduced bark beetle epidemics during drought periods). As we gain a better understanding of pre-contact forest structure, the temptation will be to use this data to return forests to previous stand densities. Moving seral stands toward conditions found in old growth stands may prevent catastrophic fire as well as maintain or increase biological diversity. But restoring ecosystem process is more than just restoring patterns and historical tree densities. The long-term impacts of procedures such as thinning dense understories and prescribed burns on ecosystem processes are not explicitly known. For example, thinning may potentially reduce pest problems by lowering stand densities and relieving the potential for drought and competition-induced stress. But, such treatments also have the potential to increase pest incidence in some instances. Logging operations often damage residual trees and can increase the buildup of root disease inoculum due to saprobic survival in stumps. Scorched trees, due to hot-burning prescribed fires, may be more susceptible to bark beetle attack. Studies to elucidate the relative roles of mechanical thinning and fire on various organisms and ecosystem processes are currently underway at several locations in California. However, none of these studies are currently being conducted in the Lake Tahoe Basin.

Because of urbanization and population growth in the basin, letting "nature run its course" is clearly not an option in managing Lake Tahoe forests. It is thought that 3500 ha per year historically burned in the basin; currently less than 400 ha are underburned. Current air quality regulations will continue to influence the amount of forest land that can be burned. Even if large scale prescribed burns can be implemented, it is not clear what intensities of prescribed burns should be used to effectively mimic natural wildfires. Due to uncertainties with the long-term consequences of the current management options, scientifically-based monitoring will be critical for evaluating the efficacy of these large-scale "experiments". If true ecosystem-based management is to take place in Lake Tahoe forests, managers must design any forest treatment with the collection of scientific data in mind. Otherwise, the ability of managers in the future to adapt to changing conditions will be compromised.

Changes in Water Clarity at Lake Tahoe

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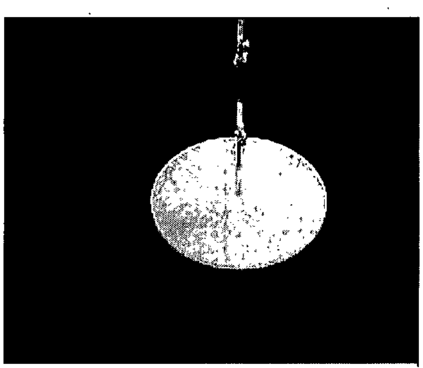
The optical clarity of water plays an important role in our casual judgments about water quality. Clarity is often used by the layperson as a basis for judging potability as well as the safety of water contact. In pristine water bodies, both freshwater and marine, optical clarity can also be an important aesthetic characteristic.

The *Secchi depth* is one common measure of optical clarity in lakes and the oceans. It is simply the depth at which an 8 or 10-inch white disc disappears from view at the surface when lowered into the water. Secchi depth measurements have been collected from many locations around the world for more than a century. Because of its apparent simplicity, the Secchi disk is sometimes dismissed as an "archaic" instrument by the novice. Quite to the contrary, it has a number of important and desirable features. First, Secchi depth is a reproducible measurement of clarity when carefully executed, more precise in fact than some electronic measures of light scattering. Second, the physics of Secchi depth measurement is well understood and Secchi depth can therefore be incorporated into rigorous predictive models. Third, Secchi depth quantifies clarity as perceived by the human visual system and is accordingly a highly suitable management endpoint for lakes. Finally, it is the only consistent optical measurement made in Lake Tahoe (and many other water bodies) that dates back several decades and can therefore be used to detect trends.

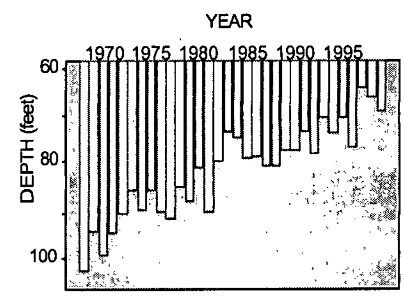


A Secchi disk just below the water surface, on its way down to check water clarity

Large clarity declines have occurred over the last few decades in some of our most transparent water bodies, including Lake Tahoe. Secchi depths of over 120 feet were recorded in the early years of the measurement program at Lake Tahoe and still occasionally exceed 90 feet. The long-term decline, though, is a matter of great concern. Overall, the decrease in Secchi depth regardless of season has averaged almost one foot per year. Because of Tahoe's unique beauty, protection of its water clarity has become an issue of pressing concern for watershed residents and the millions of annual recreational visitors.

Lake Tahoe waters have been losing transparency at an average of about one foot each year since the late 1960s.

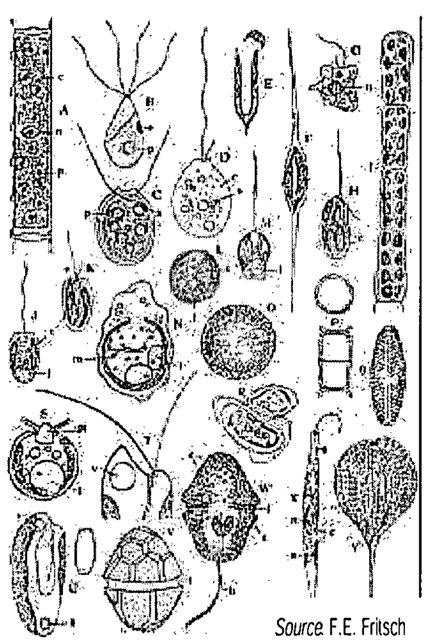
The decline in transparency is due to increases in both algae and mineral particles. Attached algae around the lake margins has proliferated over the past few decades, and microscopic drifting algae called *phytoplankton* living in the open waters has also increased. These increases have been fueled by nitrogen and phosphorus falling on the lake from the atmosphere and washing in from the watershed. In addition to these nutrients, clay and silt particles are also carried in by streams. These mineral particles, like the phytoplankton, cause light to scatter and decrease water clarity. The relative roles of phytoplankton and mineral particles are important because they determine whether the focus should be on controlling phytoplankton growth, mineral particles, or both.



The depth at which a white disk can be seen from the surface changes from year to year but generally has become shallower over the decades.

Transparency declines are due to both phytoplankton increases and to clay and silt particles washed in from the watershed.

The long time series of Secchi depth for Lake Tahoe not only records trends in water clarity but enables us to distinguish the underlying causes. Secchi depth has been measured in Lake Tahoe an average of every 12 days since July 1967. There is a marked seasonal pattern with a minimum (i.e., low clarity) in June and in December. The June low is due to accumulation of mineral particles carried in by the melting snow pack; a spring increase of phytoplankton also contributes. Generally speaking, the larger the snow pack, the bigger the decline in clarity. The December low results from the deeper and deeper mixing of the lake that starts in autumn. As the waters mix, layers of phytoplankton and other particles far below the surface are carried into upper waters where they lower the transparency. This December drop in clarity was almost nonexistent when measurements began in 1967 but it has become stronger over the years as phytoplankton growth and mineral particle inputs have increased. It is not yet fully understood how much of this long-term decrease is due to phytoplankton and how much to clay and silt. Based on the available measurements and physical considerations, both categories probably play a significant role of roughly similar magnitude.



Source F.E. Fritsch

Microscopic phytoplankton take many unique and beautiful forms. Their exact contribution to the clarity decrease depends on their size, shape, and chemical composition, as well as their abundance.

Because of the large funds to be spent in the Tahoe Basin for protecting water quality, the relative importance of phytoplankton and mineral particles needs to be resolved more precisely. Management strategies to control algae and to control soil erosion are quite different. In addition, the size distribution of particles entering and within the lake needs to be determined. Long-term clarity losses due to mineral particles are dependent on a certain size fraction, namely the fraction that will be retained in the lake and contribute to a buildup of light-scattering particles. It will be of no help to control 99% of erosion if the microscopic particles most responsible for the clarity decline are still entering the lake. Finally, the time it takes for mineral particles to clear from the lake – their *residence time* – needs to be determined. Insofar as mineral particles contribute to the long-term loss of clarity, the recovery time for the lake is dependent on this residence time. All of these issues are part of the current focus of the Tahoe Research Group at UC Davis.

The relative importance of phytoplankton and mineral particles needs to be resolved for an effective management strategy.

Additional scientific information can be found in the following publications:

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