Chapter 4: Water Quality[1]

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Introduction

Lake Tahoe is a unique environmental treasure that has been designated by the state of California (in 1980) as an Outstanding National Resource Water under the federal Clean Water Act. However, the lake's hydrologic and air basins are part of a changing landscape, with substantial portions of this once pristine region now urbanized. Studies during the past 40 years have shown that many factors have interacted to degrade the Lake Tahoe basin's air quality, terrestrial landscape, and water quality. These factors include land and forest disturbance, increasing resident and tourist populations, increasing recreational use, habitat loss, air pollution, fire suppression, soil erosion, roads and road maintenance, and loss of natural landscapes capable of detaining and infiltrating stormwater and snowmelt runoff (e.g., Reuter and Miller 2000). As presented below, the progressive decline in lake water clarity has served as a key indicator of the decline in Lake Tahoe's historical ultra-oligotrophic condition. Moreover, many consider lake water clarity a gauge of the watershed's health as a whole.

Several decades of progressively greater disturbance in the Tahoe basin, along with increased pollutant loading, have been accompanied by a concerted effort to understand the processes that control water quality and to alert the public to the implications of allowing current trends to continue unabated. Simultaneously, during the past quarter century, numerous institutions have made substantial efforts to control these impacts, reverse the decline in lake clarity, and reduce pollutant loading to Lake Tahoe, its tributaries and its ground-water aquifers (e.g., CTC 2006; LRWQCB and NDEP 2008a, 2008b, 2008c; TRPA 2007).

The watershed approach taken at Lake Tahoe recognizes that water quality is linked to upland watershed processes and air quality as well as to the legacy of adverse impacts to terrestrial and aquatic habitats. Consequently, successful implementation of land, air, and water quality restoration projects is considered key to arresting further decline in lake clarity. This understanding precipitated

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the formulation of the Environmental Improvement Program (EIP) by the Tahoe Regional Planning Agency (TRPA) and its partners in the federal, state, and local governments, and the private sector. The EIP is a regional restoration plan that describes programs considered necessary to achieve environmental goals in the Tahoe basin (TRPA 2007).

Science has played a key role in decisionmaking within the community of resource management agencies. Hundreds of scientific papers and reports have been written on many aspects of Lake Tahoe, its watershed, and its water quality since studies first began over 40 years ago. Many of these were reviewed in Reuter and Miller (2000). Active science involvement continues, and since 2000 many new findings have been produced. For example, the Lake Tahoe Total Maximum Daily Load (TMDL) program is serving as a science-based water quality restoration plan for Lake Tahoe (LRWQCB 2008) that addresses the following issues:

- Identify major pollutant sources and, where possible, quantify loading of nutrients and sediments to Lake Tahoe.
- Determine the extent to which the load of sediment and nutrients from the watershed and air basin can be effectively reduced by management and restoration activities.
- Understand how Lake Tahoe's clarity will respond to environmental improvement efforts.

Sources of scientific information used to address these TMDL and other water quality policy issues include:

- Historical Tahoe data and analyses
- Scientific literature
- New and existing monitoring
- Laboratory experiments
- Field experiments
- Demonstration projects
- New statistical analyses
- Modeling
- Best professional judgment based on scientific information

This chapter addresses science needs for water quality in the Lake Tahoe basin. It is intended to serve as a road map for discussions with resource managers to identify those research or science projects necessary to help guide water quality management strategies and understand related ecosystem processes.

Review of Important Background Elements

Lake Tahoe is a well-studied feature of the Tahoe basin ecosystem. However, although a substantial amount of research and monitoring has been accomplished, it has only been in recent years that the institutional commitment has been made to focus this work on specific management issues, such as the Lake Tahoe TMDL program. Knowledge gaps and uncertainties about what is known still exist. Moreover, water quality restoration efforts in the Tahoe basin are expected to exceed $1 billion, so it is critical that we continue to collect data and develop new information in an organized fashion in support of future investments. This scientific information is needed so that basin agencies know which management strategies are working and which strategies are not.

Based largely on the past investigations of the University of California at Davis (UC Davis), the Desert Research Institute, the U.S. Geological Survey, and the University of Nevada, Reno, there has been substantial effort since 1998 to integrate scientific efforts at Lake Tahoe, particularly in the area of water quality. Research institutions are pursuing the integration of information at the ecosystem level and among the scientific community and managers and decisionmakers. The focus of this collaboration has been to facilitate conversion of science information into management actions. Timely feedback of research findings for Lake Tahoe restoration activities is central to an adaptive management framework. This feedback relies on the completion and communication of basic and applied research, expanded monitoring, modeling, and best professional judgment. Such efforts are best guided by a more formalized research agenda.

Our goals for this water quality research strategy are to:

- Update the Key Management Questions (KMQs) that relate to water quality on the basis of work accomplished to date, and integrate them in a manner that clearly defines how they apply to the programmatic needs of agencies.
- Identify sound science activities that will help answer remaining water quality KMQs.
- Discuss the current or anticipated levels of certainty and areas of knowledge gaps of these water quality topics with respect to policy and resource management actions.

Anticipated Water Quality Topics Requiring Additional Data, Research, and Modeling

On the basis of numerous discussions, workshops, and focused programmatic meetings between researchers and Tahoe basin agency representatives, the current water quality topics (i.e., subthemes) are listed below followed by the name(s) of the topic leaders.[5]

- Lake water clarity (John E. Reuter and S. Geoffrey Schladow, UC Davis)
- Near-shore water quality (Richard B. Susfalk, Desert Research Institute)
- Pollutant loading from urban sources (Alan C. Heyvaert, Desert Research Institute)
- Stream channel erosion (Andrew Simon, USDA National Sedimentation Laboratory)
- Water quality treatment and source controls (Alan C. Heyvaert and James M. Thomas, Desert Research Institute, and Timothy G. Rowe, U.S. Geological Survey)
- Function of upland watershed with respect to hydrology and water quality (Mark Grismer, UC Davis)
- Water quality and forest biomass management practices (Wally Miller, University of Nevada, Reno and Sue Norman, U.S. Forest Service, Lake Tahoe Basin Management Unit [LTBMU])
- Drinking water protection (Michelle Sweeney, Allegro Communications, South Lake Tahoe)
- Water quality modeling (John E. Reuter and S. Geoffrey Schladow, UC Davis)
- Influence of climate change on hydrology and pollutant loading (Robert N. Coats, Hydroikos/UC Davis)

Below, we provide information on these subthemes with regard to what we know, the associated level of certainty, knowledge gaps, and ideas for research to address remaining key water quality issues.

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[5] These sections were also informed by the following contributors: Brant Allen (UC Davis), Phil Bachand (Bachand & Associates), Clary Barreto (Tetra Tech, Fairfax, VA), Nicole Beck (2ndNature, Inc.), Sudeep Chandra (University of Nevada, Reno), Robert N. Coats (Hydroikos), Julie Etra (Western Botanical Services, Inc.), Scott Hackley (UC Davis), Michael Hogan (Integrated Environmental Restoration Services), Roger James (Water Resources Management), Theresa Jones (Nevada Department of Transportation), Steve Kooyman (El Dorado County Department of Transportation), Virginia Mahacek (Valley and Mountain Consulting), Sue Norman (U.S. Forest Service, LTBMU), Steve Patterson (Steve Patterson Consulting), Eric Strecker (GeoSyntec Consultants), Ed Wallace (Northwest Hydraulic Consultants), Russ Wigart (El Dorado County Department of Transportation), and Brent Wolfe (Northwest Hydraulic Consultants).

Water Quality Conceptual Model

Prior to the arrival of European settlers, the Lake Tahoe Watershed was thought to have operated as a heterogeneous hydrologic system. Precipitation (both snow and rain) was distributed broadly through a variety of natural conditions defined by natural topography, habitat structure, and local meteorology. Natural features in the catchment determined the degree of surface water infiltration and surface groundwater interactions. Fire, floods, and other natural disturbances (e.g., earthquakes, landslides, or avalanches) were the major forces of disturbance and could generate major releases of pollutants such as fine sediment and nutrients. However, these were likely episodic in nature, with potentially substantial intervening periods between major events. More regular, low-intensity fires and a mature forest likely translated into low-nutrient stores on the forest floor. These were the watershed conditions that supported an ultra-oligotrophic Lake Tahoe: a lake with a sustained level of exceptional water clarity (≥30 m), a lake receiving low inputs of nutrients and therefore supporting low levels of primary productivity, and a lake containing a relatively simple food web that may have substantially relied on the recycling of nutrients and carbon, rather than new inputs from the surrounding watershed.

Urbanization and other forms of infrastructure development in the Tahoe basin since the mid-1800s have contributed to a change in the natural hydrologic routing in many catchments. Development has also resulted in substantial areas of land disturbance and impervious cover, which directly affects runoff dynamics and inhibits infiltration. With this development comes a hydrologic system that tends to concentrate surface runoff and inhibit surface water–ground water interactions. Studies completed as part of the Lake Tahoe TMDL show disproportionately higher loads of fine sediment and nutrients coming from the urban-related land uses (LRWQCB and NDEP 2008a, 2008b, 2008c). Much of the urban development has occurred along the edge of Lake Tahoe, meaning that in most of these cases, there is little or no buffer between the highest source of pollution and the lake. Development, primarily inside the basin, is now thought to be responsible for many of the primary and secondary drivers of water quality (fig. 4.1).

From a water quality perspective, our contemporary understanding of the Lake Tahoe watershed is framed around the "pollutant pathway" concept. This concept follows a logical sequence of pollutant generation, transport, fate, and system response including (1) source identification, (2) transport within the watershed, (3) control and abatement, (4) loads to tributaries and the lake, (5) fate of pollutant material in the lake, and (6) assessment of water quality response. A water quality conceptual model illustrating this contemporary understanding is presented schematically in figure 4.1. This diagram is not intended to identify all the drivers

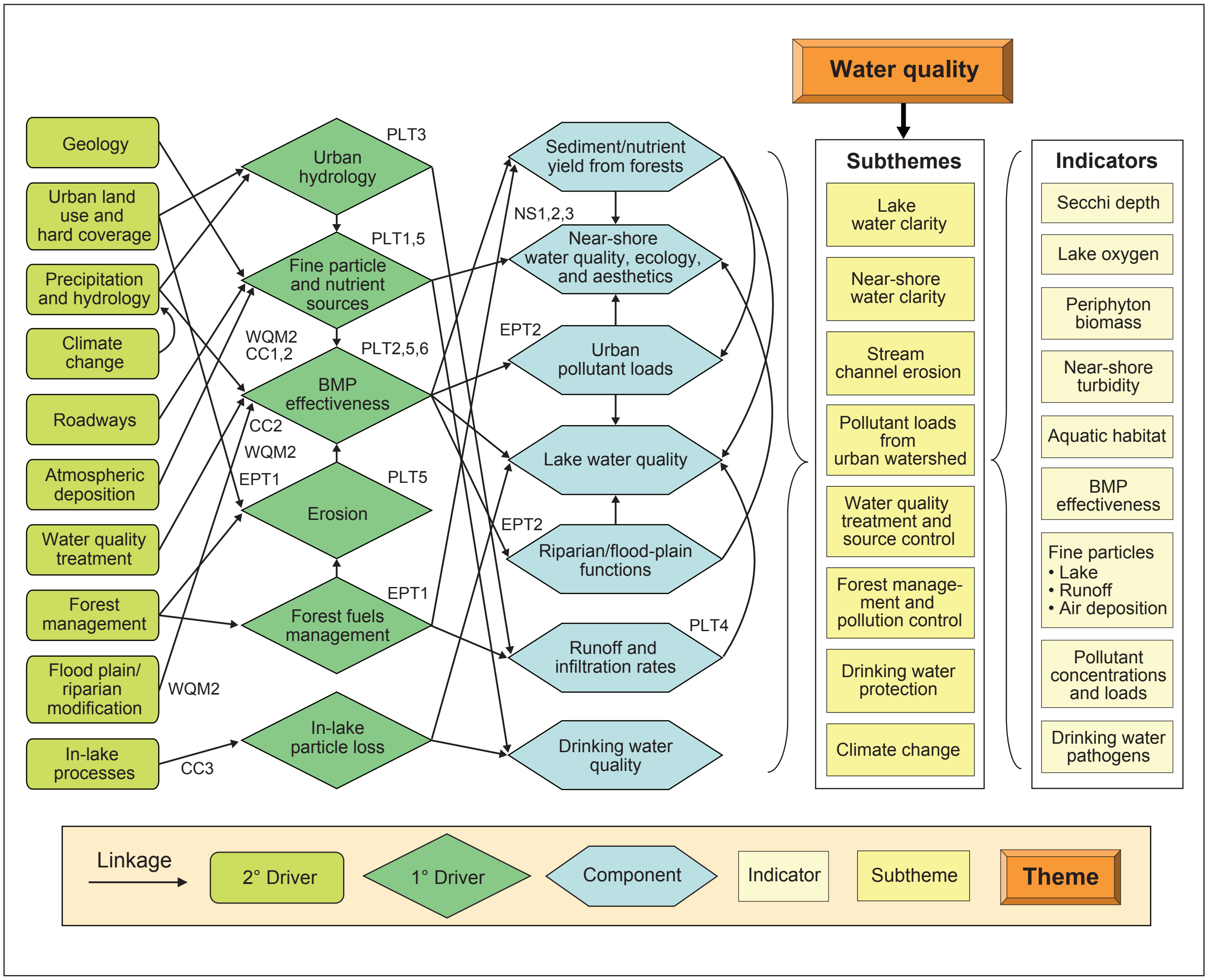

Figure 4.1—Conceptual model for Lake Tahoe water quality subthemes. This model focuses on the pollutant pathway for fine sediment particles (<20 µm) and nutrients (nitrogen and phosphorus). Key processes in this pathway include source identification, transport within the watershed, control and abatement, defining loads to Lake Tahoe, fate in Lake Tahoe, and assessment of water quality response. For ease of viewing, only key linkages are shown. BMP denotes best management practice. Near-term water quality priorities are indicated by alpha numeric symbols (e.g., WQM2, PLT3) and correspond to the descriptions presented later in the chapter.

nor show all the linkages associated with water quality at Lake Tahoe. Instead the objective is to highlight select aspects of the "pollutant pathway" while emphasizing a number of key issues that will need consideration as resource managers develop and implement pollutant reduction strategies and evaluate resultant localized and basinwide effectiveness.

Lake Tahoe Water Clarity

Long-term monitoring of Lake Tahoe water quality since the early 1960s has documented a substantial decline in clarity (fig. 4.2). In contrast, the average summer Secchi depth measurements in oligotrophic, Crater Lake, Oregon, have remained consistent showing no declining trend over the long-term.[6] The water quality standard and environmental threshold for Secchi depth[7] in Lake Tahoe is 29.7 m and is defined as the mean of annual averages between 1967 and 1971. From 1968 to 2000, there was a near-uniform decline in lake clarity as measured by Secchi depth. In some years, it seemed to improve, in other years it appeared to worsen, but invariably the trend was best defined by a straight line with an average loss in Secchi depth of approximately 0.25 m per year. However, in each of the 7 years since 2001, clarity has consistently been better than predicted by the historical data. This is unprecedented within the 40-year record. Based on the data available from

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[6] Larson, G. 2006. Personal communication. Aquatic ecologist. USGS Forest and Rangeland Ecosystem Science Center, 777 NW 9th Street, Suite 400, Corvallis, OR 97330.

[7] Secchi depth or Secchi disc depth is one technique to measure the clarity of a water body and has been used in limnology for over 100 years. Secchi depth is determined by lowering a 25-cm-diameter white disk into the water body. The mean depth at which the disk disappears and then reappears into view by a ship-board observer is taken as the Secchi depth.

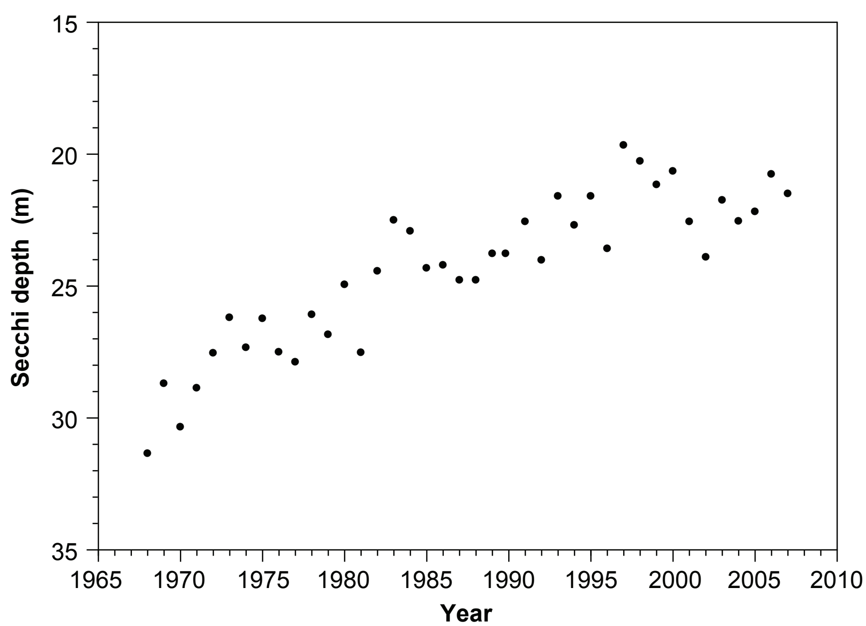


Figure 4.2—Long-term Secchi depth data from Lake Tahoe. Each value represents the annual, time-weighted average based on approximately 25 measurements per year. Date collected by Tahoe Environmental Research Center, University of California Davis.

Jim Markle

Clear, cobalt-blue-colored water of Lake Tahoe.

1968 to 1982, Goldman (1985) predicted that by 2007, the average annual Secchi depth in Lake Tahoe would be approximately 16.5 m, unless there was a change in the rate of clarity loss. During the period 2001–07, the actual annual Secchi depth measurements ranged from 20.6 to 23.7 m. Although these data do not pinpoint a specific cause for the recent change in trend, one possibility is that water quality improvement efforts targeting primary and secondary drivers (fig. 4.1) may be showing a benefit.

Secchi depth in Lake Tahoe is controlled by the light absorption and scattering properties of particles. The influence of particle number on clarity can be seen in data collected from Lake Tahoe (fig. 4.3). Earlier investigations focused on increased phytoplankton productivity as the primary source of these particles (e.g., Goldman 1994, Jassby et al. 2001). The long-term increase of primary productivity in Lake Tahoe has been attributed to increased nutrient loading acting in concert with the efficient recycling of nutrients (Goldman 1988).

The finding that fine inorganic particles (<16 μm diameter) from soil and dust contributed to lake clarity decline is a fairly recent development (Jassby et al. 1999). This finding was immediately followed by the first comprehensive study of particle number, size, and composition in Lake Tahoe (Coker 2000). Typical particle size distributions for over 40 samples from long-term lake monitoring stations show that inorganic particles <5 μm in diameter compose the majority of inorganic material in the water column during both summer and winter (fig. 4.4).

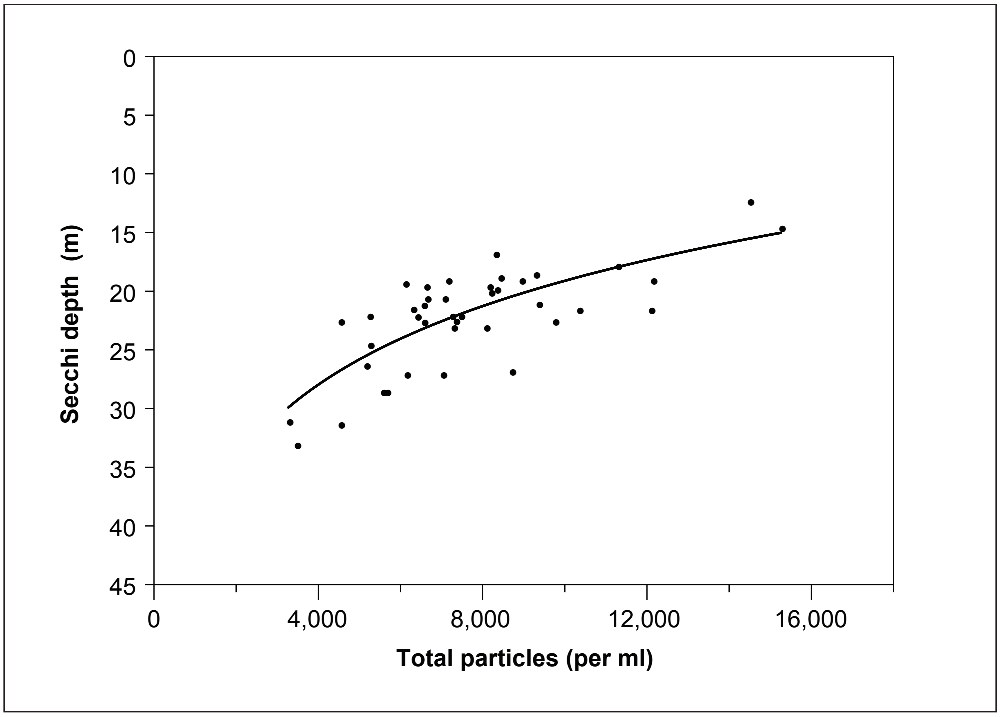


Figure 4.3—Relationship between in-lake particle number and Secchi depth (from Swift 2004). $P < 0.001$, $r^2 = 0.57$. Each point represents a single measurement of Secchi depth and particle concentration.

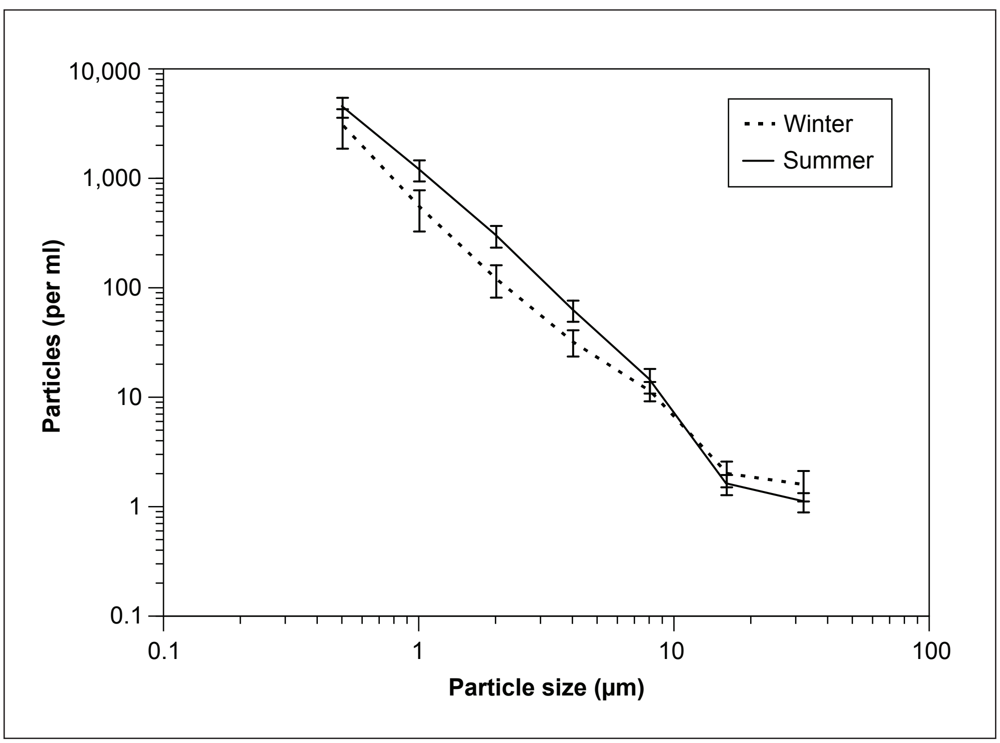


Figure 4.4—Particle size distribution in Lake Tahoe water samples showing dominance of particles <5 µm in diameter (from Swift et al. 2006).

Coker's (2000) investigation has been followed by a series of studies, examining the spatial and temporal distribution of particle concentration and composition in Lake Tahoe (Sunman 2001), characterization of biotic particles and limnetic aggregates in Lake Tahoe (Terpstra 2005), lake particles and optical modeling (Swift 2004, Swift et al. 2006), and distribution of fine particles in Lake Tahoe streams (Rabidoux 2005).

Particle loss to the lake bottom through sedimentation is critical to any mass balance consideration of particle concentration in the water column. This was confirmed by Jassby (2006) who studied particle aggregation and developed a preliminary version of a particle loss submodel. Data from Sunman (2001) suggest fine particles can be transported through the upper 100 m of the water column in approximately 3 months.

Because of efficient biotic mineralization and recycling, however, the nitrogen (N) and phosphorus (P) associated with the lake particles have a longer residence time in the water column than do the particles themselves. Mean settling velocities for N and P, as measured with large-sediment traps deployed in Lake Tahoe, were found to be 16.4 and 12.0 m per year, respectively (data from A. Heyvaert found in Reuter and Miller 2000). These rates correspond to decadal-scale settling times. With an average depth of over 300 m and a maximum depth of over 500 m, many of the nutrients associated with particles are mineralized by bacteria and effectively recycled before settling to the bottom (Paerl 1973). Note that although N and P are recycled back into the water column for use by algae, the inorganic particles that scatter light are not degraded and most settle to the bottom.

Swift (2004) and Swift et al. (2006) developed an optical submodel for Lake Tahoe to link particles and Secchi depth. The submodel takes into account algal concentration, suspended inorganic sediment concentration, particle size distribution, and dissolved organic matter to predict Secchi depth. It was found that both biological (e.g., phytoplankton and detritus) and inorganic (terrestrial sediment) particulate matter (PM) were contributors to clarity loss in Lake Tahoe. The high light-scattering properties of small inorganic particles mean they are the dominant cause of reduced light transmission. Specifically for Lake Tahoe, the optical submodel lends support to the earlier hypothesis (Jassby et al. 1999) that inorganic particles are the major determinant of clarity for most of the year. In winter, when mixing of the deep chlorophyll layer occurs, high algal levels in the surface waters result in greater attenuation by organic particles. Of the inorganic particles, it is the finer fraction (<16 μm) that is responsible for almost all of the light scattering (fig. 4.5). By relating organic and inorganic suspensoid concentrations in the lake to a predicted Secchi depth, the optical submodel has become a critical management tool.

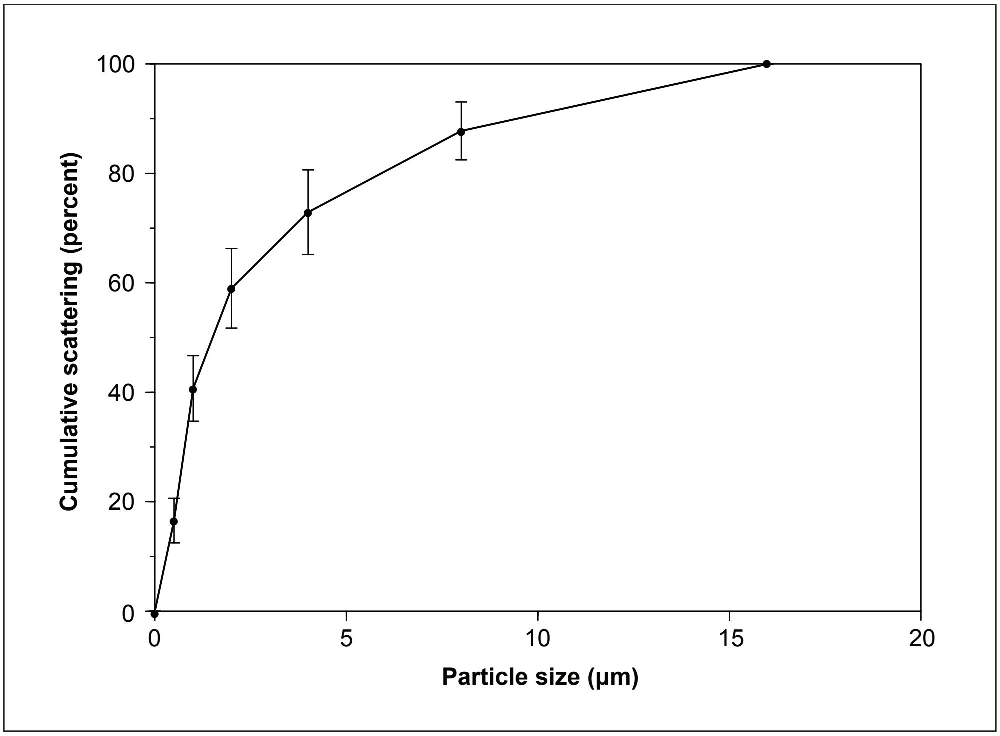


Figure 4.5—Cumulative contribution to the scattering coefficient, b_{ip}, for each of the particle size ranges. The influence of the 16 to 32 µm size range was negligible and is not included in this plot. The full 0.5 to 16 µm size range shown represents the following individual size bins, 0.5 to 1, 1 to 2, 2 to 4, 4 to 8, and 8 to 16 µm (from Swift et al. 2006).

The Lake Clarity Model (LCM) released in 2006 yielded preliminary estimates on levels of nutrient and fine sediment reductions needed to achieve the water quality standard of 29.7 m. The LCM is a combination of the optical submodel, a hydrodynamic submodel customized for Lake Tahoe, an ecological submodel, and a particle fate submodel developed as part of the Lake Tahoe TMDL science program (Perez-Losada 2001, Sahoo et al. 2009). The model contains 31 parameters covering the general areas of algae, light extinction, nutrient utilization, settling, chemical reactions, sediment fluxes, zooplankton, and inorganic particles. Nutrient and fine particle loading inputs came from studies of ground water, atmospheric deposition, surface runoff from streams and intervening zones, and stream channel and shoreline erosion (LRWQCB and NDEP 2008a).

Based on model simulations and a quantitative investigation of pollutant load reduction opportunities, a reasonable load reduction target to reach the 29.7 m water quality standard for Secchi depth would combine a 65-percent reduction for fine sediment particles (from all sources combined) with a concomitant 35-percent and 10-percent load reduction in P and N, respectively (LRWQCB and NDEP 2008c).

Changes in lake trophic (food web) status are now being documented (Chandra et al. 2005, Vander Zanden et al. 2003), and a significant shift in phytoplankton community structure has also been observed (Hunter 2004, Winder and Hunter 2008). Microbial food web grazing impacts on phytoplankton density and size structure are not known.

Lake Tahoe's annual average clarity can vary substantially from year to year based on nutrient and fine sediment loading (Jassby et al. 2003). This type of variation has been observed at other times in the long-term data record and strongly suggests lake response to load reduction can be rapid, provided a substantial level of reduction is achieved. As reported by Heyvaert (1998), lake water quality was nearly restored to prehistorical conditions within about 20 to 25 years after mass disturbance from clearcut logging during the Comstock era ended in the late 1800s. As the basin was allowed to heal, lake conditions also recovered (fig. 4.6). Although there is evidence that the lake can respond to reduced pollutant loading; the Comstock era disturbance was a pulse disturbance, primarily owing to a single stressor, i.e. clearcutting, and the lake recovered when it ended. Currently, however, there are multiple stressors at play in the Tahoe basin and disturbance is chronic. Restoration of lake water quality will ultimately depend on an active program that reduces chronic loading from urbanized and disturbed landscapes and air deposition over the long term.

Knowledge Gaps

A very large effort began in 2001–02 as part of the Lake Tahoe TMDL program to develop management tools for determining lake clarity response based on reductions in pollutant loads. Although this work has largely been successful, (LRWQCB and NDEP 2008a, 2008b, 2008c) knowledge gaps remain. Given the focus on restoration in the Tahoe basin, these initial recommendations apply primarily to improvement of the LCM and its application for management purposes.

Some of the key uncertainties regarding Tahoe's water clarity include:

- Atmospheric deposition of particles onto the surface of Lake Tahoe, the fate of these particles upon entering the water, and subsequent impact on clarity. This topic and associated research needs are covered in more detail in the "Tahoe Basin Meterology" section of chapter 3.
- Characterization, distribution and dynamics of particles in Lake Tahoe's water column, beyond the initial studies completed in the early 2000s. This includes new methodologies for measuring lake optical properties and in situ particle characterization, and developing a better understanding of the relationship between ultraviolet light transmission and lake particles.

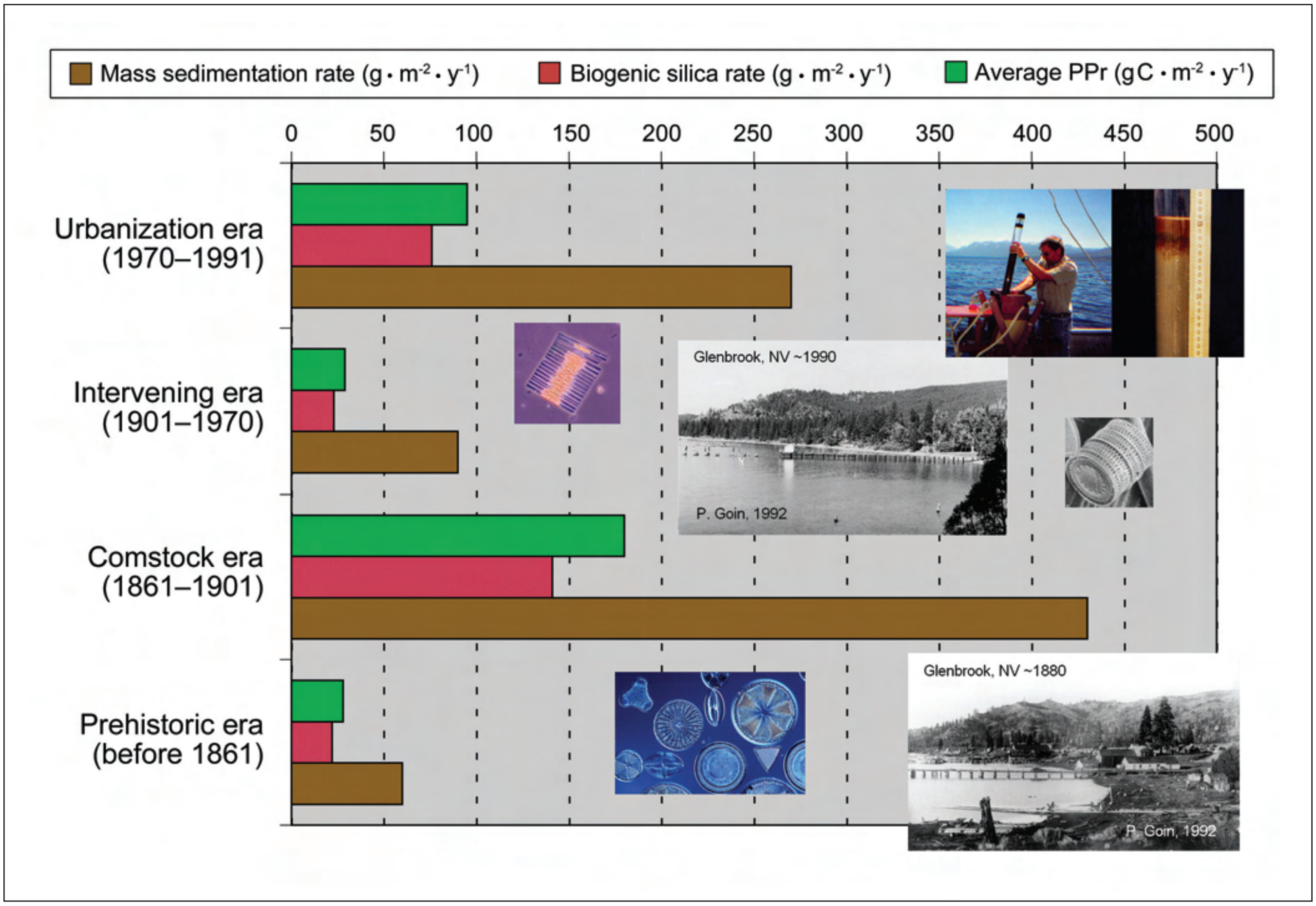


Figure 4.6—Summary of paleolimnologic studies that reconstruct the recent water quality history of Lake Tahoe (from A. Heyvaert, Desert Research Institute). Mass sedimentation includes all material, both biogenic and abiotic. Biogenic silica is derived primarily from diatoms and provides an estimate of sedimentary material from this algal group. PPr denotes phytoplankton primary productivity.

- Rates of particulate matter (PM) sedimentation, mechanisms of nutrient loss, and dynamics of size-specific particle removal from the water column. This also includes the dynamics of very fine particles with regard to coagulation and aggregation, and lake-water equilibrium chemistry.
- Plankton and bacterial food webs and the importance of the "microbial loop" in regulating the fate of particulate organic matter. Macroscale food webs, i.e., large zooplankton, benthic invertebrates and fish, are considered in the "Aquatic Ecosystem Integrity" section of chapter 6.
- Biogeochemistry of biologically available nutrients.
- Mechanisms underlying the specific relationships between pollutant loading and load reduction, and lake clarity response.

Research Needs

Characterization, distribution, and dynamics of particles in Lake Tahoe's water column—

Extensive measurements in Lake Tahoe during the first few years of the 2000s provided a new understanding of particle characterization and distribution. This was the first time such measurements were made and allowed us to ascertain some of the fundamental properties of these particles. Inorganic particles have been associated with the regulation of optical properties in lakes; however, with only a few notable exceptions worldwide, limnologists have not focused on this topic to the level needed at Lake Tahoe. Consequently, there is sparse literature to draw upon.

Particles affect lake clarity as a result of the manner in which their number, composition, location, and shape affect scattering and absorption of light. The relationship between particle loading, biogeochemistry, physical forces that determine the position of particles in the water column, and processes that remove particles to the lake bottom are complex and have not been fully studied. There is also uncertainty associated with dry and wet deposition of particles onto the lake surface via atmospheric deposition. Further, the LCM is very sensitive to particle sedimentation processes, and the biological parameters were taken from literature values rather than from Tahoe-specific research. Our knowledge of phytoplankton and bacterial ecophysiology and lake nutrient cycling also is limited.

The following investigations are considered important during the next 5 years. These investigations are intended to (a) update and refine the LCM, (b) determine baseline conditions for particles from which sound statistical assessments of long-term response to restoration efforts can be evaluated, (c) assist in the development of a sound environmental monitoring program, and (d) provide critical supporting data for concurrent studies of particle loss characteristics.

- Research is needed to establish a statistically based monitoring program to evaluate particle number, particle size distribution, seasonality of particle distribution, position of particles in the water column, particle composition, and particle shape as it affects clarity. In situ approaches for measuring particle distribution and lake optical properties are being developed. Application of such approaches (e.g., use of UV light attenuation profiles as a surrogate for particle density, or deployment of particle probes) would benefit from research and testing. Development of common methodologies is recommended to produce comparable data as part of any particle monitoring program, whether it be specifically for the water column in Lake Tahoe or other sources of particles (e.g., streamflow or urban runoff).

- Remote sensing needs to be evaluated for large-scale (whole-lake synoptic) measurements of clarity, including particles and other factors affecting lake clarity.
- Further investigation of particle loading from all upland sources is recommended to determine specific sources, loading rate characteristics based on size and composition, and characteristics of transport. Sources of particular interest include land use type, activities on the landscape (e.g., road sanding or sweeping), parent soil characteristics, vegetative cover, slope, and other factors. Determination of physicochemical fingerprints of particles for comparison to upland materials is one example of an approach to identify specific sources of loading to the lake.
- The influence of "black carbon" on lake clarity has not been quantified. Black carbon represents those particles that result from combustion of organic matter (e.g., biomass burning and diesel exhaust) and enter the lake through atmospheric deposition. Additional research is needed on the optical properties of these particles in water; their numbers, size and distribution in the water column; rates of dissolution and loss; and their ultimate effect on clarity.

Mass sedimentation rates, nutrient loss, and mechanisms of size-specific particle sedimentation—

Loading and transport of particles to Lake Tahoe is an area where substantial new research, monitoring, and modeling is recommended. Focusing specifically on the lake itself and important processes in the water column, our knowledge of mass sedimentation rates, nutrient loss, and size-specific settling, is still not complete—uncertainty exists.

Previous studies of mass/bulk sedimentation in Lake Tahoe come primarily from work by Marjanovic (1989) and Heyvaert (1998). Installation and maintenance of in situ sediment traps is needed to evaluate long-term sedimentation rates and compositional characteristics. Chemical and biological analysis of the settled material allows us to better understand the quantitative and qualitative aspects of PM loss. For the mass balance approach taken in modeling, it is equally important to have sufficient information on particle loss as on particle loading. In the time allotted to develop the LCM for the TMDL, emphasis was placed on particle loading as it also gave insight into what control options would be most effective. It is recommended that additional scientific attention now be placed on the loss terms of the model.

Particles typically enter Lake Tahoe as discrete units. The production of extracellular products, the formation of biofilms, and other biological processes (largely mediated by bacteria and algae) play a substantial role in the aggregation, coagulation, and settling of particle complexes (Logan et al. 1995). Coagulated material is able to settle much faster than individual particles. Results of the LCM show that these processes are crucial to the removal of particles from the water column and, in fact, the loss of aggregated PM can be rapid. The very initial aspects of these types of studies was recently started (Jassby 2006); however, more detailed investigations are recommended.

Bacterial and plankton food webs and their influence on biological particles— An extensive literature has documented the importance of bacteria, pico-phytoplankton (0.2 to 2 µm), and the microbial food web in oligotrophic waterbodies (e.g., Callieri and Stockner 2002). The presence of the microbial food web in oligotrophic oceans and lakes was first documented about 20 years ago. A substantial portion of the nutrient and carbon cycling and energy flow in oligotrophic systems typically pass through this microbial loop (e.g., Azam et al. 1983). It is suspected that an important portion of the lake's primary productivity results from pico-phytoplankton, but definitive information is lacking.

The effect of bacteria, pico-plankton and the microbial food web could not be expressly quantified in the LCM, so assumptions were made. The influence of the microbial community on nutrient cycling, as well as the direct effect on biologic particles via production and grazing, and the indirect effect on inorganic particles (e.g., aggregation and coagulation processes) all warrant additional research. These studies take on additional significance given the recent findings that climate change and its effect on lake temperature may be influencing phytoplankton community structure (Winder et al. 2008).

Assessment of biologically available nutrients—
Biologically available phosphorus (BAP) was measured as part of the TMDL science program. Although this study included a variety of potential P sources, it was not extensive with regard to spatial and temporal characterization. However, the TMDL scope of work was intended to provide the LCM with values for BAP that were not simply taken from the literature. In this regard it was a successful project that for the first time provided an initial understanding of the importance of BAP (Ferguson 2005, Qualls 2005). Now that relationships have been established between BAP and chemical assessment techniques, BAP portioning for specific P sources are recommended. In addition, a better understanding of P availability and P cycling in Lake Tahoe would help improve the LCM.

For P in particular, bioavailability can be affected by lake-water equilibrium chemistry. Depending on the in-lake concentrations and the magnitude associated with particulate matter, this nutrient can either be stored in PM and fine inorganic sediments, or it can leach into the surrounding water. Characterization of P-leaching rates associated with these processes is likely to be dependent on particle size and composition, and further research is recommended to update the relevant water quality components of the LCM.

Organic N loading in the streams monitored through the Lake Tahoe Interagency Monitoring Program (LTIMP) typically accounts for >90 percent of the total N load, with about 50 percent of the organic N present in the dissolved form (Coats and Goldman 2001). Dissolved organic N is also abundant in wet and dry fallout from atmospheric deposition accounting for 25 to 30 percent of the total N load from this airborne source (LRWQCB and NDEP 2008a). Clearly, the fraction of the organic N pool that is bioavailable can have a substantial influence on algal growth as well as on our efforts to model this process. Biologically available N (BAN) is a difficult research area requiring experience, very specialized techniques, and a laboratory that is set up for these types of measurements. Only a limited number of research groups nationally are conducting such studies. Although an extensive BAN study is not necessarily recommended at this time, a feasibility study evaluating the potential impact of uncertainty associated with the lack of direct BAN measurements at Tahoe, vis-à-vis algal growth and lake clarity, is strongly suggested.

Statistical relationships between pollutant loading and lake clarity response— Statistical analysis of historical Secchi depth measurements, and the development of a statistically-based mechanistic model for evaluating long-term and interannual variability in Lake Tahoe's clarity, have provided significant insights regarding changes in Lake Tahoe's optical properties (e.g., Jassby et al. 1999, 2003). A statistical approach is recommended to determine when improvements in Secchi depth clarity and other measures of light transmission in Lake Tahoe occur. In particular, managers would benefit from science-informed criteria for determining the influence of pollutant load reduction on clarity. This would include determining the significance of short-term variation on clarity, and—given the natural degree of interannual variability—the number of years of data that would be required before agencies know if their management milestones have been met.

Update of Lake Clarity Model and linkage to other pollutant source and management models—

Based on the knowledge obtained from all research topics conducted in the Tahoe basin, we recommend specifically allocating funding to update the LCM to accommodate new data and insight. Additionally, linking existing and new management models (e.g., Tahoe Watershed Model, Water Erosion Prediction Program [WEPP], Lake Tahoe Atmospheric Model, Conservational Channel Evolution and Pollutant Transport System [CONCEPTS], Pollutant Load Reduction Model [PLRM] and/or ground-water modeling) to each other and to the LCM is desired by resource managers and the scientific community. As discussed in the "Climate Change and Water Quality" section (p. 155), the LCM is also considered an important research tool in evaluating the effects of climate change on lake stratification, water quality, and aquatic ecology.

Lake Tahoe Near-Shore Water Quality

The near-shore zone of Lake Tahoe is one of the most visible components of the Tahoe ecosystem to both tourists and local residents, and a decline in near-shore water quality is more readily apparent to the largely shore-bound population. The near shore is part of the littoral zone: that portion of a lake where enough light reaches the bottom for macrophytes (rooted plants) and periphyton (attached algae) to grow. At Lake Tahoe, the littoral zone frequently extends to depths greater than 40 m, and can extend 20 m to several kilometers out from the shore line, depending on bottom topography. Processes within the near shore exhibit spatial and temporal variability owing to their response to and integration of onshore activities, events within the near shore, timing and magnitude of channelized (stream), and unchannelized (surface) runoff, and the mixing with and dilution by mid-lake waters.

The response of the near shore to pollutant loading is more immediate than mid-lake waters owing to the near shore's proximity to the terrestrial environment and its shallow nature. Erosion and disturbance in the upper watersheds (including shallow ground-water flow) often manifests along the lake shore in terms of increased periphyton growth, decreased water clarity, higher nutrient concentrations, greater abundance of easily suspended sediments, and increased macrophyte growth. Near-shore water quality also influences higher order biological species that inhabit this region. Anecdotal information from long-term residents and visitors suggests near-shore aesthetics have substantially deteriorated over the last several decades, including but not limited to excessive periphyton growth, increased turbidity, and establishment and expansion of Eurasian watermilfoil (*Myriophyllum spicatum*) and other introduced species.

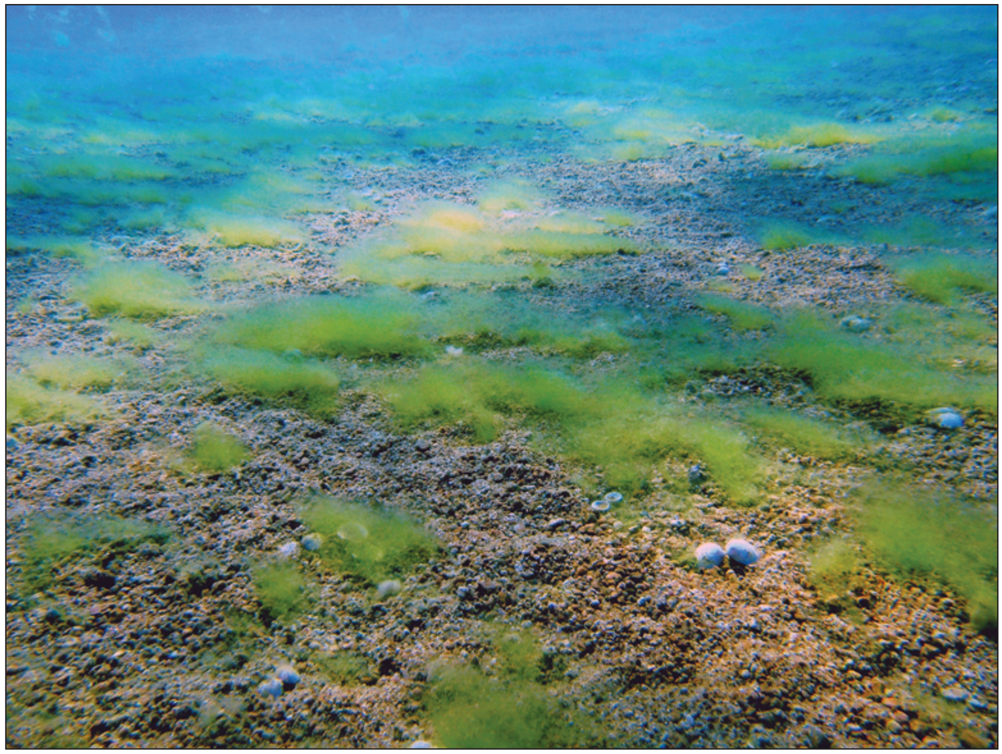
Jim Markle

Undeveloped near-shore habitat near Sand Harbor, Lake Tahoe.

Research on Lake Tahoe's near-shore zone has not historically received the same level of attention that watershed and mid-lake processes have received. Studies that have investigated the near-shore zone have found processes and characteristics that are highly dependent on location and adjacent watershed activities and timing. For example, eulittoral periphyton communities located in the shallow area between high and low lake levels exhibit large seasonal variation, whereas sublittoral periphyton located in the remainder of the littoral zone exhibit less seasonality (Loeb and Palmer 1985). Some information is also available on near-shore water clarity, periphyton, fish and benthic communities, and currents and circulation patterns (e.g. Beauchamp et al. 1994, Hackley et al. 2007, Herold et al. 2007, Kamerath et al. 2008, Loeb et al. 1983).

Studies that have assessed spatial variability in the near shore show decreased clarity and increased periphyton biomass associated with greater development and disturbance in the adjacent onshore watershed. Taylor et al. (2004) found near-shore water clarity along 7 km of shoreline ranged from moderately to highly impaired, and 4 km of shoreline was slightly impaired. These authors also reported large reductions in clarity near developed areas immediately after summer thunder-storms, during winter lake-level snowmelt events, and during the seasonal spring snowmelt. This observation highlights the adverse impacts of hydrologic events acting on urban landscapes. Increased nutrient loading from urbanized watersheds

Brant Allen



Metaphyton (*Zygnema* sp.) growing on the shells of nonnative clams (*Corbicula fluminea*) in the near shore at Elk Point, Lake Tahoe.

stimulates periphyton biomass (e.g., Hackley et al. 2004, 2005, 2007); however, there also have been instances of elevated periphyton biomass found off pristine (nonurbanized) watersheds, suggesting littoral zone currents also play a role in determining near-shore conditions.

Questions exist as to whether current regulations are adequate, and if the regulations recognize the large spatial differences in near-shore water quality. There are also questions about our level of understanding of near-shore water quality: What are the trends in near-shore water quality, and what are the important processes controlling near-shore water quality? Ultimately these questions focus on generating the information necessary for determining the policies needed to protect this critical recreational resource and its natural resources. As discussed above, previous and current studies in the near-shore region of Lake Tahoe have provided us with some understanding of near-shore water quality. However, most of these studies have been done as separate investigations—a more holistic approach that is fully integrated with management information needs (similar to that being taken for mid-lake clarity) would provide resource and planning agencies with the type of knowledge they need when making policy decisions regarding the near shore.

Knowledge Gaps

Some of the key uncertainties regarding Tahoe's near-shore water quality include:

- The lack of baseline data needed to develop a comprehensive understanding of the near-shore ecosystem that can inform management strategies and support environmental thresholds. The existing patchwork of studies investigating near-shore processes and stressors has not been sufficient to sustain a consistent baseline data collection effort. Continued research and monitoring is necessary to assess long-term trends, to better understand near-shore processes, and to develop quantitative near-shore water quality standards. Data from such a program are invaluable and could be used to inform the following knowledge gaps:
    - Response of the near shore to watershed restoration and management activities. It is unknown if the reduction of nutrient and sediment sources currently being planned and implemented will mitigate near-shore impairment. Monitoring of near-shore characteristics is needed to better understand the effectiveness, results, and potentially unintended consequences of onshore treatments (e.g., stormwater infiltration basins installed near the lake shore).
    - The potential direct and indirect effects of future near-shore development and boating scenarios (e.g., piers and buoys) on near-shore ecology and water quality.
    - The impacts that changing/managed lake level has on near-shore water quality, periphyton communities, and habitat.
    - The information base agencies need to establish informed water quality standards, and environmental thresholds and indicators that will be protective of near-shore water quality and aesthetics.

- It is important to recognize and improve our understanding of the roles that spatial variation plays in near-shore processes. The spatial variability of conditions in the near shore is very complex owing to the interactions among a suite of land-based and lake-based processes. The near shore can be roughly divided on the basis of depth (eulittoral or splash zone and sublittoral) and urban versus undeveloped. Near-shore habitats also differ around the lake owing to factors such as embayments, marinas, open water, and bottom substrate type. Lastly, the near-shore zone is also impacted by the variability found within adjacent onshore watersheds (e.g., soils and land use) and the circulation and mixing patterns with the deeper waters of the pelagic zone. Examples of existing knowledge gaps include:

  - Limited information exists on the distribution and quantity of periphyton at a basinwide scale. This information is necessary to provide a regional context and sufficient basis for basinwide biomass estimates and predictive tools.
  - There is little current knowledge on the degree to which urbanization has impacted the near-shore zone. Short- and long-term urbanization impacts may or may not exceed natural spatial and temporal variations. Information on the impacts of urbanization is needed so that thresholds and standards can account for the differences between pristine and urbanized areas.

- A greater knowledge of the linkages between processes within and external to the near-shore zone are needed to understand the ability of the near-shore zone to propagate watershed impacts into the pelagic lake zone. The near-shore zone is a dynamic buffer that integrates nutrient and sediment outputs from adjacent terrestrial watersheds, atmospheric deposition, processes within the near shore, and mixing with deeper lake waters. Specific knowledge gaps include:
  - Limited understanding of the near-shore capacity to assimilate terrestrial outputs without adversely affecting water quality, clarity, and ecology.
  - The inability to predict how near-shore physical processes will respond to onshore and littoral zone management actions. For example, will onshore erosion control differentially alter the loading of dissimilar particle size classes to the lake in a way that would negatively impact near-shore habitat characteristics?
  - Limited understanding of the manner in which physical processes (e.g., currents, wave action) control the dispersion, accumulation, spatial distribution, and transport of pollutants and plankton, both within the littoral zone and between the littoral and pelagic zones.

Research Needs

Research is needed to better understand near-shore processes at various temporal and spatial scales. This research is best accomplished so that it contributes to an integrated database, which can be used to determine trends and patterns for integrated, process-driven models. This research would further develop our understanding of the linkages between near-shore and mid-lake processes. Ideally, this new information would be linked directly to management decision models and could inform the development of appropriate thresholds and management strategies for Lake Tahoe's near-shore environment.

A science-based risk analysis of stressors to the near-shore environment is also an important research need. It is recommended that this analysis take a comprehensive, ecosystem approach, and evaluate the full suite of stressors that could affect near-shore water quality (both environmental and human health), as well as the ecology, recreation, and scenic values. Following are examples of more specific scientific inquiry and data collection efforts that are needed to inform Lake Tahoe near-shore water quality and ecology management.

The need for baseline data of near-shore characteristics to support management strategies and thresholds—

- It is recommended that these data could include nutrient sources and cycling (through tributary, direct runoff, ground water, lake mixing), physical processes affecting the littoral zone (e.g., lake circulation and currents, wave activity, changes in lake level, benthic substrate type), and biological variables (e.g., grazing, sources of algal colonization, or abundance and distribution of native and invasive species).
- Assess near-shore "hot spots" for water quality impacts, and evaluate contributing factors. Are "hot spots" related to upland activities (e.g., urbanization), or do they reflect impacts from near-shore facilities such as marinas or public beaches?
- Synthesize existing monitoring data to develop recommendations for numeric near-shore water quality targets for nutrients, fine sediment particles, lake optical properties, periphyton, and aquatic plants.

Analysis of the roles that spatial variation plays in near-shore processes—

- Improve estimates of spatial variability in the near shore by developing remote sensing methods that can detect local and regional changes in water clarity and periphyton growth. Assess potential remote sensing methods for accuracy, limitations, and compatibility with existing methods.
- Determine the levels and spatial distribution of near-shore phytoplankton and periphyton production using field (observational and experimental) and modeling studies.
- Develop a basinwide database and predictive models to understand how physical, biological, hydrologic, and nutrient factors control periphyton communities in Lake Tahoe. For example, how is storm-water infiltration and loading to the lake via ground-water discharge affecting near-shore water nutrient loading?