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An Integrated Science Plan for the Lake Tahoe Basin: Conceptual Framework and Research Strategies

Editors

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Front cover: Lake Tahoe view from Mount Rose Highway scenic pullout, looking northwest toward Tahoe City, California. Back cover: Lake Tahoe view from Mount Rose Highway scenic pullout, looking south. Both photographs by Peter Goin.

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Chapter 4: Water Quality[1]

John E. Reuter,[2] James M. Thomas,[3] and Alan C. Heyvaert[4]

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.

[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 ground-water 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

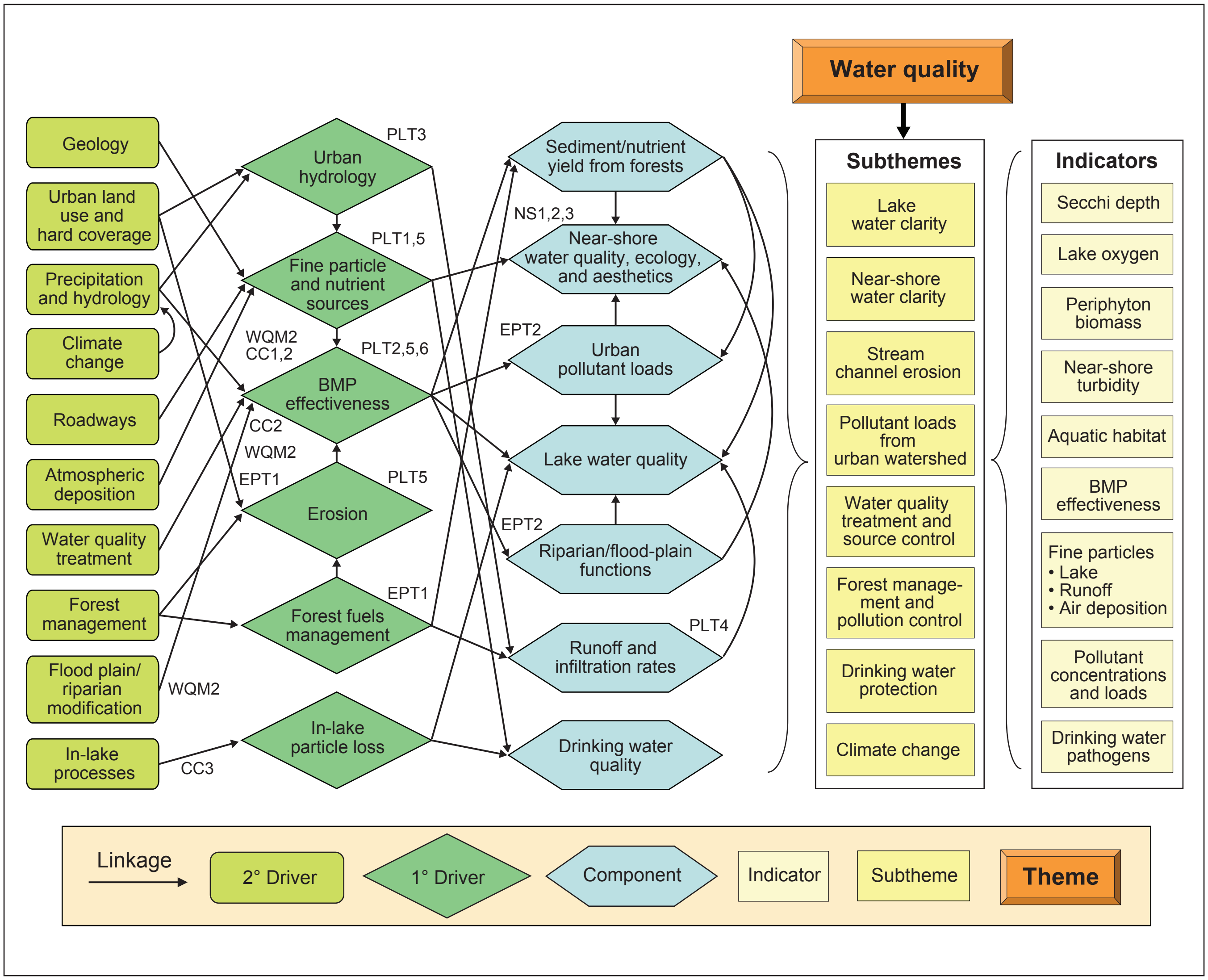

Figure 4.1—Conceptual model for Lake Tahoe water quality subthemes. This model focuses on the pollutant pathway for fine sediment particles (<20 µm) and nutrients (nitrogen and phosphorus). Key processes in this pathway include source identification, transport within the watershed, control and abatement, 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.

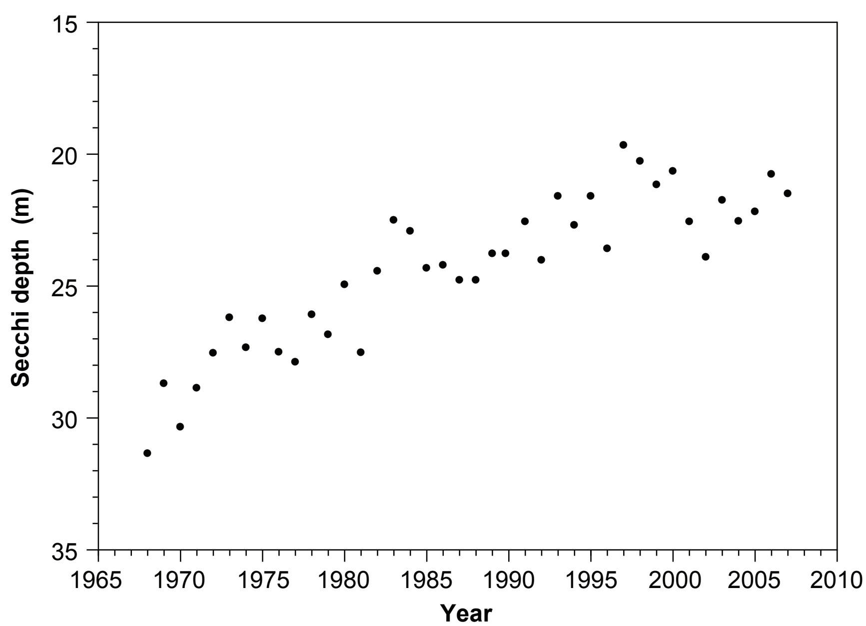


Figure 4.2—Long-term Secchi depth data from Lake Tahoe. Each value represents the annual, time-weighted average based on approximately 25 measurements per year. Date collected by Tahoe Environmental Research Center, University of California Davis.


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).

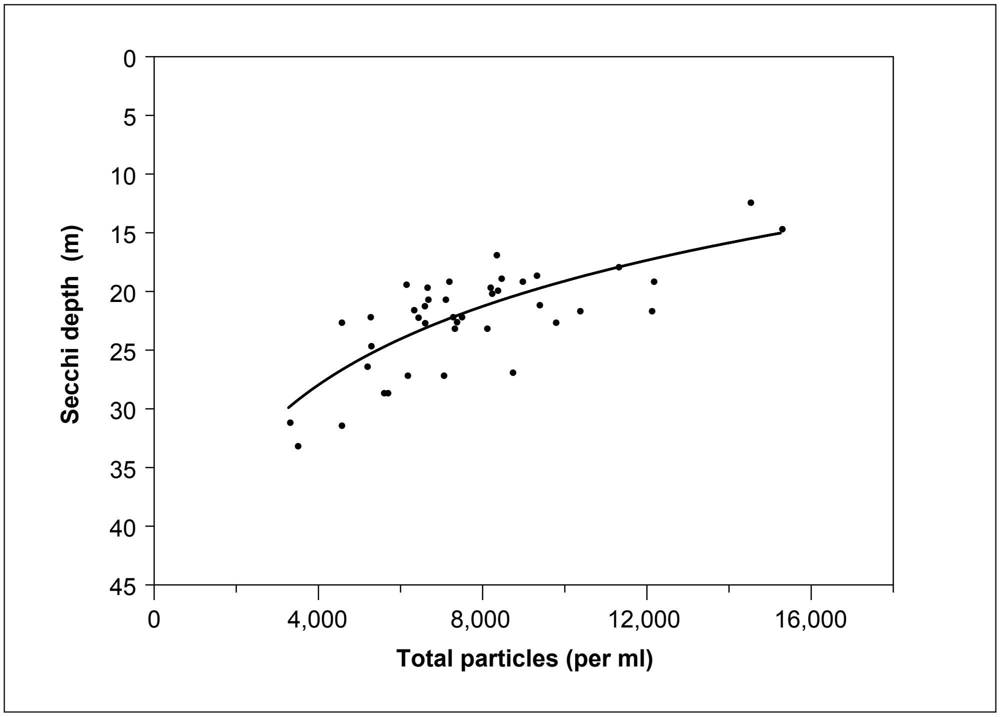


Figure 4.3—Relationship between in-lake particle number and Secchi depth (from Swift 2004). $P < 0.001$, $r^2 = 0.57$. Each point represents a single measurement of Secchi depth and particle concentration.

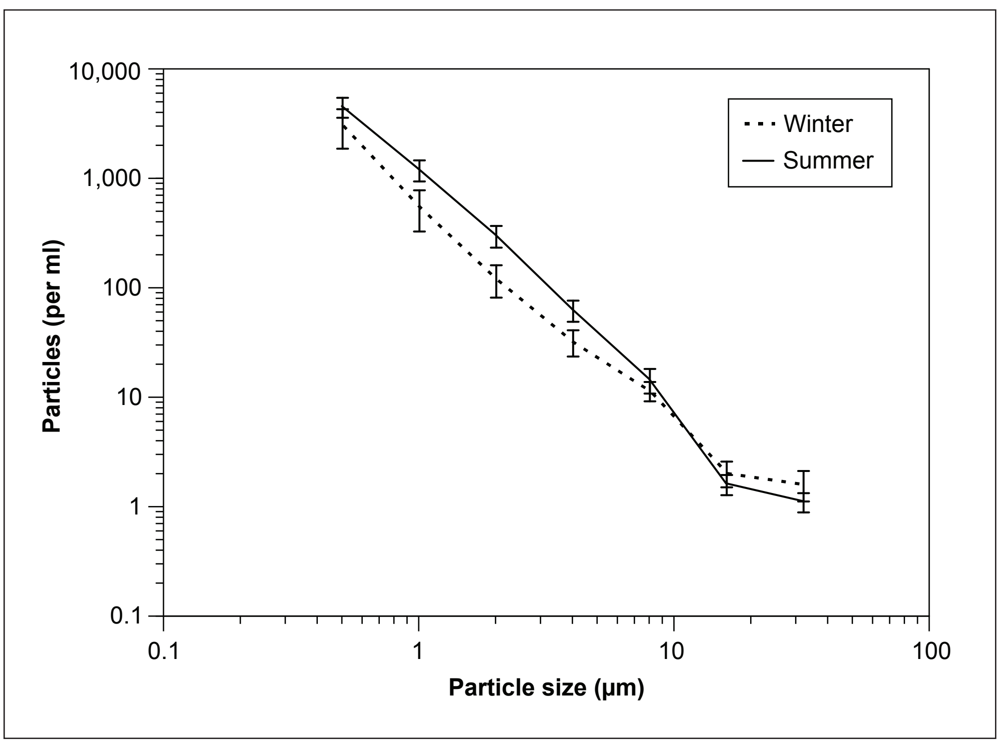


Figure 4.4—Particle size distribution in Lake Tahoe water samples showing dominance of particles <5 µm in diameter (from Swift et al. 2006).

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.

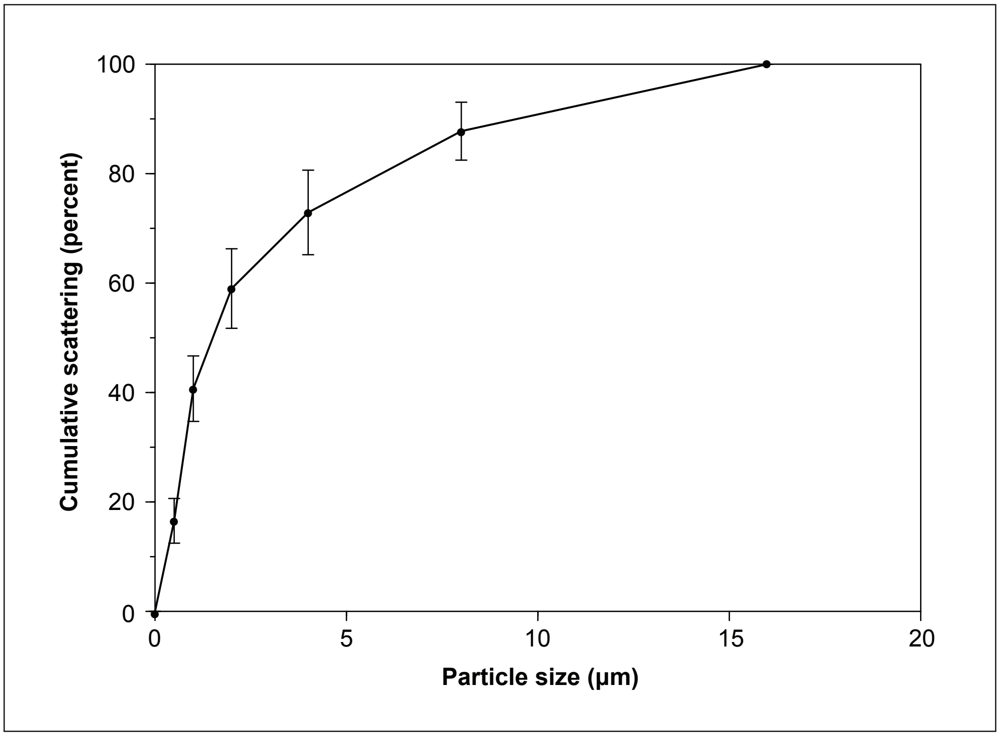


Figure 4.5—Cumulative contribution to the scattering coefficient, b_{ip}, for each of the particle size ranges. The influence of the 16 to 32 µm size range was negligible and is not included in this plot. The full 0.5 to 16 µm size range shown represents the following individual size bins, 0.5 to 1,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

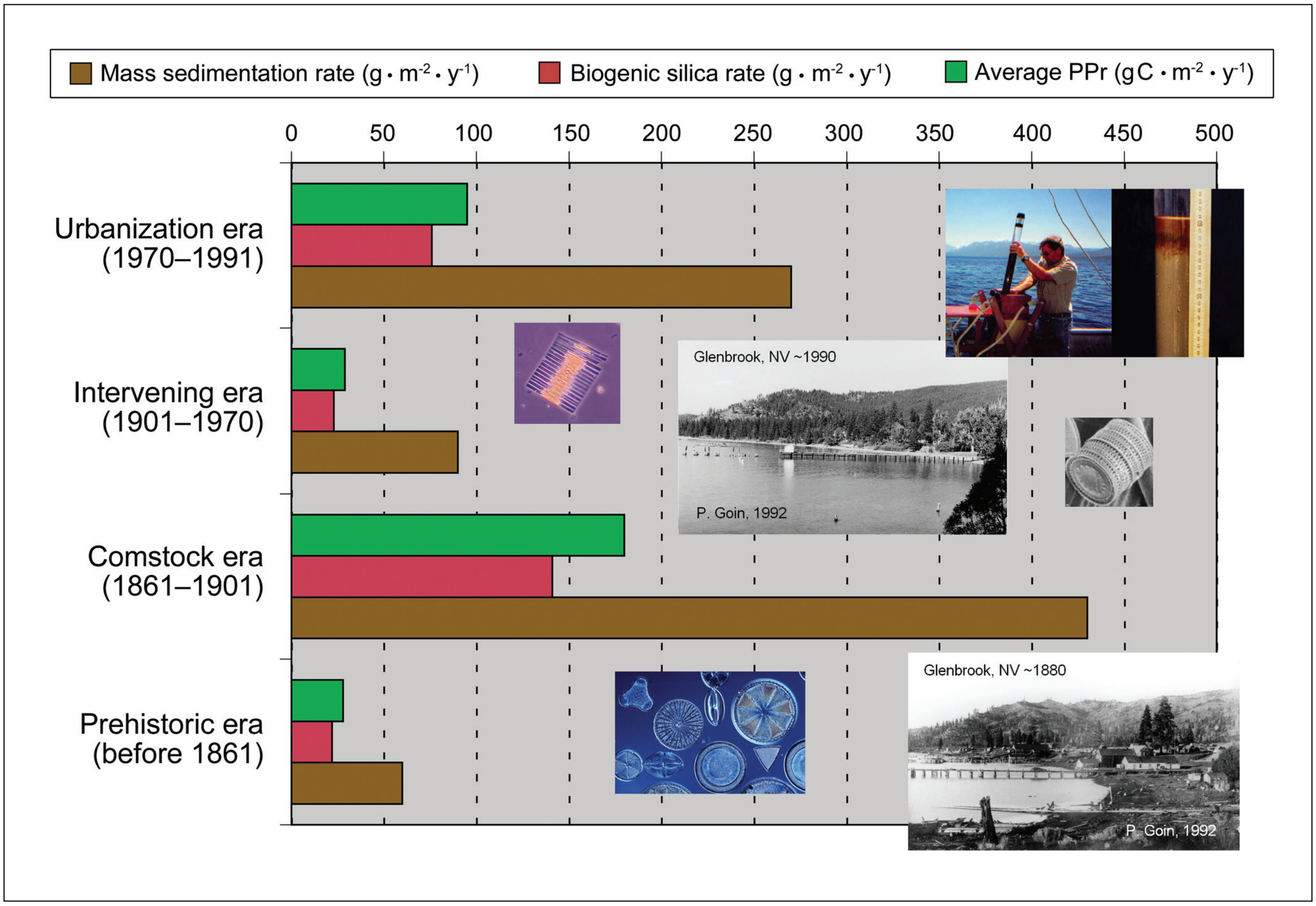


Figure 4.6—Summary of paleolimnologic studies that reconstruct the recent water quality history of Lake Tahoe (from A. Heyvaert, Desert Research Institute). Mass sedimentation includes all material, both biogenic and abiotic. Biogenic silica is derived primarily from diatoms and provides an estimate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

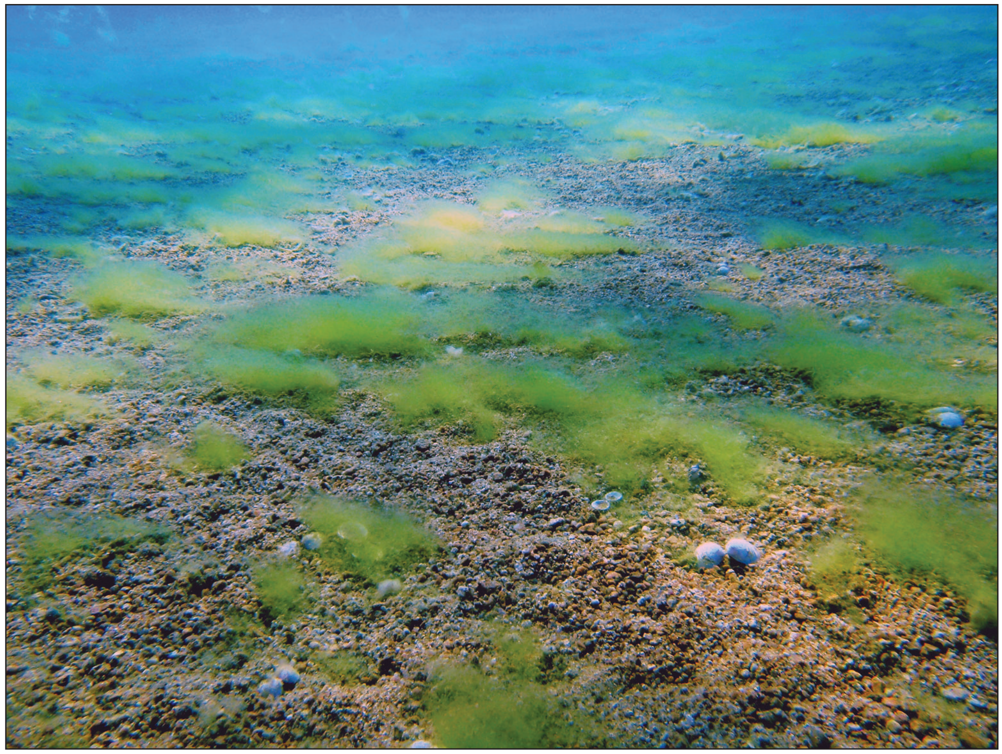
The response of the near shore to pollutant loading is more immediate than mid-lake waters owing to the near shore's proximity to the terrestrial environment and its shallow nature. Erosion and disturbance in the upper watersheds (including shallow ground-water flow) often manifests along the lake shore 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.

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?

- Determine how changes in lake level affect near-shore processes, including shoreline erosion.
- Evaluate how hardening (reinforcement) of shore zones affects the near-shore environment. For example, how are erosion, deposition, and transport of near-shore sediments, hydraulics of wave run-up, and geomorphic processes affected by shore zone hardening?
- Develop a coarse-sediment mass budget for the near-shore environment. Is enough sediment being delivered to maintain beaches and near-shore habitat characteristics?

Define and assess the linkages between on-shore, near-shore, and mid-lake processes that affect water quality, clarity, and ecology—

- Define and create the tools to (1) simulate the transport of pollutants within the near shore and around the lake and (2) predict the ability of the near shore to buffer and propagate pollutant loading from onshore activities to mid-lake.
- Further refine/quantify the role of the near shore as an integrator of watershed, atmospheric, and mid-lake processes. Can a change in near-shore characteristics be used as an indicator for short-term, neighborhood-scale activities or as a long-term indicator for water impairment?
- Develop analytical approaches for generating quantitative water quality standards, thresholds, and indicators for the near-shore region.

Pollutant Loading From Urban Sources

Results of water quality monitoring show that for some urban land uses (e.g., roads and commercial development), the concentrations and loads of pollutants in surface runoff can be substantial. Although estimated flow from urban areas is only part of that from nonurban areas, the inputs of pollutants from these areas are 50, 60, and 72 percent of the total annual loads to Lake Tahoe for N, P, and fine particles (<16 µm), respectively (LRWQCB and NDEP 2008a).

Relative Contribution of Sediment Loading From Urban Sources

A number of studies have been completed over the past 30 years to address sediment delivery issues from various watersheds in the Tahoe basin. However, these studies have (1) generally focused on only a few streams within the watershed (Glancy 1988, Kroll 1976, Nolan and Hill 1991, Stubblefield 2002), and (2) usually considered only the larger category of total suspended sediments, rather than focusing on the finer fractions. More recently, studies have begun to examine the loading of total suspended sediment mass, along with suspended sediment mass for material <63 µm, and the number of particles for <16 µm sediment fractions (LRWQCB and NDEP 2008a, Sahoo et al. 2007, Simon et al. 2003, Tetra Tech 2007).

It is instructive to compare estimates of sediment loading to the lake from all sources, including the urban landscape (table 4.1). These results illustrate the importance of fine-sediment particle loading (number of particles) derived from urban sources.

Table 4.1—Total suspended sediment (TSS) and fine particle loading to Lake Tahoe for the major pollutant sources[a]

Pollutant source	TSS		TSS <63 µm		Particle number[b]	
	Metric tons/year	*Percent*	*Metric tons/year*	*Percent*	*<20 µm/year*	*Percent*
Urban upland runoff[c]	5,200	17	4,430	31	34.80×10^{19}	72
Nonurban upland runoff[c]	11,700	40	4,670	33	4.11×10^{19}	9
Stream channel erosion[d]	5,500	19	3,800	27	1.67×10^{19}	4
Atmospheric deposition[e]	NA	NA	750	5	7.45×10^{19}	15
Shoreline erosion[f]	7,200	24	550	4	0.11×10^{19}	<1
Total	29,600	100	14,200	100	48.14×10^{19}	100

[a] Values are expressed as metric tons/year (metric tons = 1000 kg) except for particle number, which is expressed as number of particles <16 µm/year (taken from LRWQCB and NDEP 2008a).
[b] Percentage values refer to the relative portion of total basinwide load.
[c] Upland runoff (urban and nonurban) is the annual mean value from measurements collected between 1994 and 2004.
[d] Stream channel erosion is the annual mean value from measurements collected between 1983 and 2002.
[e] Atmospheric deposition is a combined estimate of wet deposition (annual mean value from measurements collected between 1992 and 2003) and dry deposition (measured in 2003 only).
[f] Shoreline erosion represents a 60-year mean annual value.
NA = not applicable.

The total suspended sediment (TSS) loading from all major pollutant sources was estimated to be approximately 29,600 metric tons per year (MT/yr) (LRWQCB and NDEP 2008a). Upland watersheds, including stream channel erosion, account for 22,400 MT/yr, and represent 75 percent of the TSS load. Upland watersheds without the contribution from stream channel erosion, deliver 16,900 MT/yr, of which 5,200 MT/yr or 30 percent was generated from the urban portion of these watersheds. Shoreline erosion contributes on average about 7,200 MT/yr; however, it is likely that this source is highly variable from year to year, and the total erosion rate between 1938 and 1998 was affected by some very large events (Adams and Minor 2002). Stream channel erosion from both urban and nonurban stream sections combined was independently estimated at 5,500 MT/yr (Simon et al. 2003).

For the TSS <63 µm size fraction ($TSS_{<63\ \mu m}$), it was estimated that average annual loading to Lake Tahoe was 14,200 MT/yr from all sources (LRWQCB and NDEP 2008a). This accounts for nearly 50 percent of the total TSS loading. Upland runoff contributed 9,100 MT/yr, or 63 percent of the $TSS_{<63\ \mu m}$ load. The $TSS_{<63\ \mu m}$ loadings from urban and nonurban areas were virtually identical, at about 4,500 MT/yr. However, the loading ratio of TSS to $TSS_{<63\ \mu m}$ differed between urban and nonurban land use categories. For urban areas, approximately 85 percent of TSS load was in the $TSS_{<63\ \mu m}$ fraction, whereas only 40 percent of the TSS load from nonurban areas was contributed by this smaller size fraction. The contribution of TSS and $TSS_{<63\ \mu m}$ from the other major measured sources is shown in (table 4.1).

The first estimates of fine particle loading to Lake Tahoe in terms of particle numbers have only recently become available (LRWQCB and NDEP 2008a). These estimates were based on studies by Heyvaert et al. (2008), Rabidoux (2005), CARB (2006), Tetra Tech (2007), Sahoo et al. (2009), and Adams (2002). As discussed previously, although loading estimates for TSS and the $TSS_{<63\ \mu m}$ fractions are of interest, it is the fine particles <16 µm that are of greatest concern, as these have the most effect on lake water clarity.

The average annual load of fine particles <16 µm from all major sources was on the order of 5×10^{20}. Table 4.1 shows the estimated breakdown of loading by source categories for particle numbers in the <16-µm size range. Approximately 85 percent of the <16-µm size particle loading into Lake Tahoe is associated with surface runoff from urban and nonurban upland sources, including stream channel erosion. By far the most significant contributor was urban runoff, accounting for 72 percent of total lake loading for fine particles <16 µm. In contrast, the nonurban uplands only accounted for 9 percent of the fine particle loading, and stream channel erosion only accounted for 4 percent. It is very interesting to note that as the sediment size classification becomes smaller (i.e., from TSS to <63 µm to <16 µm particles), the relative contribution from urban areas increases substantially. Urban TSS load was estimated to be 17 percent. This nearly doubled to 31 percent for the <63-µm fraction and more than doubled again to 72 percent for the <16-µm particle number loads. Relative contributions from nonurban sources generally declined with decreasing particle size, except atmospheric deposition where loading from <16-µm size particles increased to 15 percent of the total.

Sources of fine sediments in urban areas of Lake Tahoe also include gully erosion from roadside ditches, upstream sediments that are more efficiently passed through urban drainage systems and concentrated in discharges, fine particulates washed off urban surfaces (including applied sanding materials, break-pad wear, or air deposition), and downstream erosion caused or accelerated by urban runoff discharges that exceed natural runoff conditions.

Urban Hydrology

Much of the existing urban stormwater drainage system around Lake Tahoe was installed as part of subdivision development many decades ago, when the main purpose of drainage system design was to provide efficient stormwater conveyance and flood control, with minimal design considerations given toward downstream water quality effects. Currently, insufficient hydraulic retention exists within many urban drainages. Instead, culverts and ditches generally concentrate and expedite runoff from urban watersheds into receiving waters. As a consequence, peak flows at most storm frequencies are much higher than would occur without urban development; these higher peak flows not only facilitate pollutant transport, they also enhance erosion within urban watersheds.

Runoff rates and volumes are sensitive to the amount of impervious surface area and its connectivity to drainage systems. Existing regulations on new development focus on the onsite retention and infiltration of runoff from impervious surfaces, and substantial investments are being made to retrofit existing development with new best management practices (BMPs) and public drainage improvements.

Alan Heyvaert

Urban stormwater discharge to the Upper Truckee River at Highway 50.

These BMPs are usually designed to accommodate the 20-year storm (equivalent to about 2.54 cm of precipitation in 1 hour). Although this approach may be adequate for designing individual BMPs, managing urban stormwater quality at Lake Tahoe will depend on a fully integrated understanding of the existing pathways of urban drainage on a subwatershed scale. Without a better understanding of the degree of connectedness between pervious and impervious parcels within the drainage in a subwatershed, estimating load reduction for the purpose of the TMDL will be done for individual projects in isolation and will ignore the connectivity along the pollutant pathway defined by regional hydrology.

Land Use and Runoff Water Quality Relationships

Our understanding of land use-water quality relationships in the Tahoe basin is based on five sources (1) the data collected since 1978 by the LTIMP (Coats et al. 2008, Rowe et al. 2002); (2) the recently completed Lake Tahoe TMDL Stormwater Monitoring Study (Coats et al. 2008, Gunter 2005); (3) the Tetra Tech LSPC (Loading Simulation Program in C++) hydrology-water quality model recently developed for the Lake Tahoe TMDL (Riverson et al. 2005), (4) the Pollutant Load Reduction Model (NHC 2009), and (5) process-based studies of nutrient and sediment sources and transport in subalpine watersheds in and near the Tahoe basin (e.g., Coats and Goldman 2001; Hatch et al. 2001; Heyvaert and Parra 2005; Heyvaert et al. 2006; Johnson et al. 1997; Merrill 2001; Miller et al. 2005; Murphy et al. 2006a, 2006b; Sickman et al. 2002; Simon et al. 2003; USFS 2004).

The designation of land use groups was a critical first step in developing watershed-scale estimates of pollutant loads under the Tahoe TMDL (LRWQCB and NDEP 2008a). Land uses have been grouped into 20 categories for the Tahoe basin. The second critical step in characterization of land use-runoff relationships was the estimation of runoff volumes for each land segment. This estimation was done using the Tetra Tech LSPC watershed model with hourly weather data and land-segment-specific hydrologic parameters that have been measured, estimated, or calibrated to reflect the unique characteristics of watersheds around the lake. In the Lake Tahoe watershed LSPC model, event mean concentration data from the TMDL Stormwater Monitoring study were used to model characteristic runoff water quality from different urban land use types. An event mean concentration (EMC) is a calculation used to provide a flow-weighted concentration for a pollutant in question that summarizes conditions during a defined stormwater runoff event. The EMC multiplied by total flow during a stormwater runoff event is taken as the estimated load during the event. For primary roads, the EMCs were developed using a combination of Caltrans and Nevada Department of Transportation (NDOT) monitoring data. Runoff sediment and nutrient loads were estimated by applying EMCs to modeled runoff volumes. The characteristic EMCs and load estimates can differ substantially by land use, region, soil type, and season of the year (e.g., Coats et al. 2008).

Based on the studies described above, it is known that compared to undisturbed and naturally functioning forested lands, the urbanized areas produce much higher concentrations of ammonium-N, nitrate-N, total N, orthophosphate, total P, and also in some cases, suspended sediment. There are also large differences in the yield rates (loading per unit area) of nutrients and sediment for different watersheds in the basin (LRWQCB and NDEP 2008a, Tetra Tech 2007).

In general, for the 10 watersheds sampled as part of the LTIMP (Rowe et al. 2002) the relative concentrations of N and P forms decrease in order: organic-N > nitrate-N > ammonium-N; and total P > dissolved P > orthophosphate. In some urbanized areas, the ammonium-N can be a significant fraction of total N load, whereas it is generally insignificant for watersheds containing little urbanization (Coats et al. 2008, Gunter 2005).

The concentrations and loads of nutrients and sediment are directly related to impervious surface area. In developed areas, the concentrations of P (orthophosphate and dissolved P) are generally related to percentage of residential impervious area, although N concentrations (nitrate-N, ammonium-N, and organic-N) are directly related to the density of multifamily residential lots (LRWQCB and NDEP 2008a). Suspended sediment concentrations are directly related to percentage of area in commercial-industrial-communications-utilities land uses (Coats et al. 2008, Gunter 2005).

Stream channel erosion is a source of TSS in the Tahoe basin streams (see table 4.1), and as noted above, channel erosion can be exacerbated by increased runoff from urbanized areas. Discharge-concentration relationships in basin streams differ greatly among constituents, and with season (Rowe et al. 2002). This variability strongly influences the accuracy and precision of load estimates. Orthophosphate concentrations are strongly controlled by equilibrium reactions with the substrate, and do not change greatly with discharge. Nitrate-N is influenced by biological release and uptake, and by an annual washout cycle, with high autumn and low spring concentrations. The concentrations of particulate constituents (e.g., total P and TSS) are both flow and supply-driven, and vary by orders of magnitude throughout the year.

Role of Highway Surfaces and Shoulders on Pollutant Runoff

Highway surfaces represent about 15 percent of total impermeable surface area in the Tahoe basin. Yet, because of the large number of vehicle miles traveled on these surfaces and the hydraulic connectivity that these routes provide, they often contribute stormwater runoff concentrations that are much higher than observed from other distributed land use types. This is particularly true for fine-particle concentrations in roadside runoff. The Lake Tahoe TMDL has identified that over 50 percent of the fine particles (<16 µm) may originate from the basin's extensive network of primary and secondary roads.

Highway and road runoff typically contain high concentrations of fine sediment, presumably from the abrasive action of traffic on roads and roadside soils and on winter traction materials applied to road surfaces. Traffic and parking on road shoulders in particular, causes considerable damage to the vegetation and the soils surrounding most roads. This compaction increases runoff as well as the loads of sediments and fine particles.

The optimal conditions for fine particle settling include long hydraulic residence time and minimal water movement. Unfortunately, the size/area requirements for construction of optimal BMPs are usually not feasible alongside most roadways, given their limited rights-of-way, terrain constraints, and sensitive environments. Installation of large underground vaults generally is not practical either because of utilities, traffic, and maintenance requirements. These systems also require ready access and easy maintenance to ensure effective long-term functioning. Therefore, new approaches are being sought for treating highway runoff to the level required in the Lake Tahoe basin.

Source control measures are necessary to help prevent sediment from becoming entrained in highway and urban runoff. Revegetation and soil restoration success, however, can be limited by factors that include the dry summer climate at Lake Tahoe, steeper topography, and nutrient-poor soils. In some cases, armoring of highway cut and fill slopes is a successful alternative with appropriate applications and dispersed runoff flows.

Recreational Impacts

There are three types of recreational facilities that can result in accelerated erosion and runoff. These consist of native-surface roads and trails, developed recreational facilities (e.g., visitor centers and trail heads), and established recreation sites (e.g., campgrounds and ski areas). Developed recreational facilities generally exhibit the same features and impacts typical of other urban development (e.g., parking lots and buildings). Forest roads and trails, ski runs, and campgrounds, however, all have unique characteristics that increase their potential sediment and nutrient loading into receiving waters if appropriate BMPs are not properly installed and maintained.

The major risks to water quality from forest road and trail networks exist on those road segments that are hydrologically connected to stream crossings. So proximity of roads and trails to stream channels is the single greatest concern related to road/trail impacts on water quality. Between 2002 and 2005, the Forest Service implemented a forest road BMP retrofit program to reduce the connected length of roads, particularly at stream crossings. This program has decommissioned approximately 150 km of roads, and has conducted BMP retrofits on 241 km of roads. In 2005, the USFS initiated a similar retrofit program for trails. The effectiveness of both programs has been under evaluation (USFS 2002). Based on this work, it is now understood that maintaining the efficacy of the BMPs typically applied to native surface roads and trails requires a high frequency of maintenance. However, preliminary monitoring results also indicate a substantial reduction in the potential for erosion and transport of sediments as a result of efforts to retrofit, upgrade, and decommission forest roads in the Tahoe basin.

A decade of monitoring at Heavenly Ski Area indicates substantial improvement can be achieved at ski areas in relation to water quality, soil condition, erosion control, and sediment transport (USFS 2004).

Knowledge Gaps

Urban hydrology—

Urban hydrology in the Tahoe basin is complicated by the fact that developed communities are relatively small, and highly influenced by runoff from wildland regions that are immediately adjacent and often located within the urban boundaries. Although models are used for uniform runoff computations for designing specific BMPs and runoff conveyance features in the Tahoe basin, no attempt has been made to comprehensively model flow from its upland source through all the urban features (including specific BMPs and water conveyance features) and finally into Lake Tahoe or one of its tributaries. Furthermore, project-specific models for BMP-related runoff computations are generally not well calibrated, and the effects of rain on snow have been difficult to estimate. Precipitation and flow monitoring data are scarce in urban areas of the basin. Our understanding of snow hydrology in urban areas and its contribution to seasonal runoff patterns also is limited. The Pollutant Load Reduction Model is a recent attempt to more accurately estimate runoff from project areas. However, it would benefit from more specific data.

Land use and runoff water quality relationships—

The uncertainty associated with estimates for loads and concentrations is not well-determined. Specifications for two kinds of error are recommended. The first is sampling error associated with taking instantaneous samples of continuous concentration variables. The second is prediction error associated with regression estimates based on the relationships between concentration and discharge. Despite some published data (e.g., Loupe 2005, Meidav 2008, Miller et al. 2005) there is also considerable uncertainty associated with the runoff from vegetated land use categories, representing a large part of the Tahoe basin.

Role of highway surfaces and shoulders on pollutant runoff—

The contribution of highway stormwater runoff and pollutant generation is not well-defined relative to total watershed impervious surface areas and the percentages of pollutants generated specifically within the road and rights-of-way. Although curb and gutter installations reduce road shoulder compaction and erosive runoff scouring, these structures generate larger runoff volumes at higher velocities. So effective alternative designs are needed to disperse roadway flows while preventing erosion. These designs also need to reduce the migration of soils and fine particles onto road surfaces, and their subsequent transport to receiving waters.

Sources and transport of fine sediment—

Because the reduction of fine particles is considered key to improving the clarity of Lake Tahoe (LRWQCB and NDEP 2008a, 2008b, 2008c), more detailed information is needed on the specific sources of fine particles and the relationships between natural watershed characteristics (e.g., geology, aspect, slope, vegetation cover), anthropogenic features (e.g., roadways, transportation/traffic, land use), and fine sediment loads from watershed drainages in urban areas.

Recreational impacts—

Increasing use and prevalence of trails around urbanized areas may be of concern, especially where hikers and mountain bikes are causing hillslope erosion, meadow disturbance, or streambank degradation. Roads may present even greater water quality concerns owing to their larger disturbance area, greater traffic volume, and larger stream crossings. Although ski run restoration has provided substantial increases in overall effective soil cover (and subsequent reductions in erosion), monitoring indicates that some areas of the mountain do not respond to current restoration practices. Therefore, better methods are still needed for maintaining vegetative cover in difficult conditions.

Pollutant transport from urban areas—
Hydrologic adjustments are still being accommodated from historical disturbances in most drainages receiving runoff from urban land uses. We need a better understanding of stable equilibrium conditions in urban drainages and streams. On a basinwide or regional scale, the extent of specific urban area erosion problems (hot spots) and their relative contribution to long-term pollutant loads is unclear. Better spatial information is needed for all urban drainage systems in the Tahoe basin, especially for those that discharge directly to the lake or to potentially erosive channels, streams, and overland flow areas.

Research Needs

Urban hydrology—

- Review and compile data from local runoff monitoring so that a Tahoe basin urban hydrologic monitoring network can be designed and implemented to provide consistent, comparable, and continuous urban flow data.
- Implementation of a Tahoe basin meteorological network is recommended to supplement existing long-term monitoring sites (SNOTEL, National Climate Data Center) and improve the utility of hydrologic monitoring and modeling.
- Conduct modeling studies of monitored catchments to identify sensitive parameters and develop appropriate calibration and parameter estimation techniques.
- Develop a coordinated modeling approach to simplify regional relationships for estimating runoff flow-duration characteristics and time series of flows from urban areas.

Land use and runoff water quality relationships—

- Conduct research to quantify fine particle and nutrient loading from nonurbanized, vegetated areas.
- With regard to urban stormwater flow, gain a better understanding of the temporal-and spatial-scale processes associated with hydrology and pollutant transport between pervious and impervious areas.
- Better assess relative contributions from specific land use sources for particular pollutants of concern, including fractionalization into the dissolved, bioavailable, and total constituent concentrations.
- Develop refined pollutant load estimates for the various land uses with a comparison of continuous and event-based modeling approaches for application to drainage and water quality project design.

- Conduct comparative water quality modeling studies in catchments where monitoring data are available or where monitoring is planned to improve our understanding of the relative importance of spring snowmelt, “first flush,” and extreme events.
- Validate models that estimate sediment and nutrient loading/load reduction from urban land uses.

Role of highway surfaces and shoulders on pollutant runoff—

- Continue monitoring stormwater from highway runoff, including assessment of sediment loads and particle size distributions, to better understand spatial and temporal variability.
- Conduct quantitative evaluations to guide appropriate curb and gutter designs or alternatives that will reduce runoff volumes and pollutant loads while limiting roadside parking and soil compaction. These recommendations could address differences in roads at higher versus lower elevations, and between urban and rural areas, as well as between different types of road surfaces.
- Conduct studies on the effectiveness of different source control measures, such as paving of roadside ditches, placing riprap on cut and fill slopes, or the revegetation of disturbed areas, especially as these practices relate to mobilization and transport of fine sediments.
- Develop better estimates for the pollutant load reduction of maintenance associated with road sand collection, sweeping, and sediment removal. Better estimates are particularly needed for fine sediments <16 µm.
- Research the development of highway runoff treatment BMPs that remove fine sediment from stormwater runoff. This research could include methods that increase fine sediment capture with new types of hydraulic structures and with the retrofit of existing structures, e.g., drop inlets and small settling basins.
- Conduct research to determine the specific size range for fine-grain sediments that are best targeted in treating highway runoff, and the amount of P that can be removed with this sediment.
- Gather more systematic information on the effectiveness of infiltration systems, given characteristics of Tahoe basin soils, and where these basins are optimally located to best treat highway runoff.

Sources and transport of fine sediment—

- Conduct comparative assessments of the various methods for determining and reporting particle-size distribution, with the goal of developing recommended uniform protocols for data analyses and for reporting results.
- Ascertain relationship between turbidity and the number of fine particles for monitoring load reduction.
- Compile and review the available monitoring data for particle-size distribution to improve estimates of loading by land use category, by drainage characteristics, and by catchment conditions.
- Conduct studies to expand understanding of particle-size distribution loads from all land use categories, including source-specific studies on anthropogenic activities that produce and mobilize fine sediments.
- Conduct trend analyses of particle-size data to describe the temporal and spatial contributions of fine-sediment loadings from dominant sources, including relative contributions.
- Complete studies on the mass of particles contributed annually from abrasive wearing of road surfaces, including the characterization of size distribution and the chemical properties of this material.
- Increase measurements of the percentage of snow traction material removed by street sweeping activities, and the amount of material remaining.
  Conduct studies to better understand the drainage characteristics of primary and secondary roads as this flow transports fine particles and other pollutants to receiving waterbodies. Determine how road sand is pulverized by tires and quantify the conversion of large particles into smaller, more environmentally relevant sizes (i.e., <16 µm).

Recreational impacts—

- Revisit high- and moderate-risk road segments that did not improve with BMP retrofits to identify the causes of failure and possible improvements. This could also address the amount of maintenance required to maintain efficacy of BMP retrofits over the long term.
- More intensively monitor ski resort impacts throughout the Tahoe basin, as is done currently at Heavenly Ski Resort. Ideally, this monitoring also would include the evaluation of soil restoration approaches being developed through the California Alpine Resort Environmental Cooperative.
- Evaluate water quality effects from low-impact techniques currently used and proposed by ski resorts in removing trees to create new glades and runs.

- Assess the distribution of impacts from trail development and use near urban areas (especially with respect to mountain bike use).
- Assess the distribution and impacts from fertilizer applications on recreational areas such as ball fields, golf courses, and public lawns.

Pollutant transport from urban areas—

- Conduct process-based studies to describe the sources, transport mechanisms, and sinks for nutrients and sediments on their journey from urban landscapes to Lake Tahoe.
- Conduct studies to better understand pollutant accumulation, transformation, and transport processes in snow and snowmelt, especially for roadway, roadside, and parking lot snowpacks. These snow and snowmelt studies could include monitoring to better evaluate pollutant release from roadside snowpack under various settings and management strategies (e.g., highway versus secondary streets, heavy versus light traction abrasive application, shade versus sun, plowing and blowing versus hauling or moving).
- Understand how new improvements will affect drainages, and what improvements are needed to allow watersheds to reach their desired equilibrium states is important. In addition to the hierarchical approach of source control, hydrologic design, and treatment is generally recommended, but alternative or complementary strategies also could be evaluated. Furthermore, it is recommended that monitoring, modeling, and project construction all occur on equivalent time scales to obtain validation data from "real" projects.
- Develop a field classification scheme for identification of specific erosion problem areas (hot spots) as sources of sediment and nutrients. Watershed and drainage inventories that map the type, extent, and condition of hot spots according to an established classification scheme would help target mitigation projects. This would lead to research and monitoring to develop estimation techniques for evaluation of erosional hot spots as sources of sediment and nutrients to downstream waters. It would be useful to understand how much of the loads and concentrations measured in monitoring data (e.g., the land use-based characteristic concentrations) are associated with erosional hot spots versus distributed sources.
- Complete of a basinwide inventory to provide detailed spatial information on the distribution of drainage systems and discharges, as well as existing downstream conditions. This inventory could address legacy as well as modern drainage and conveyance routes, and BMP installations. Local agencies have started this work.

- Develop better predictive models for evaluating the effects from disturbance and mitigation projects that change runoff paths, volumes, velocities, and patterns, especially as this relates to the potential loading of fine particulates from accelerated channel, stream, and overland flow erosion. These models could provide comprehensive watershed analysis for evaluating the best methods to reduce peak flows and pollutant loads from urban watersheds.

Peter Goin

Active streambank erosion along the Upper Truckee River, south of Highway 50.

Stream Channel Erosion

In addition to affecting lake clarity, sediment derived from stream channels can affect localized hydrology, instream habitat for lotic aquatic biota, and stream-water quality. Streambank erosion has been identified as a source of TSS from several watersheds as a result of extensive reconnaissance-level field work throughout the Tahoe basin, and by resurveying monumented cross sections originally established in the 1980s (Hill et al. 1990, Simon et al. 2003). In particular, streambank erosion in Blackwood and Ward Creeks, and the Upper Truckee River was found to be the major contributor of TSS from these watersheds (fig. 4.7) (Simon et al. 2003). Overall, the contribution of sediment (<63 µm in diameter) from streambank erosion was estimated by developing an empirical relationship between measured or simulated bank-erosion rates (adjusted for the content of silt and clay in the bank material) with a field-based measure of the extent of bank instability along given reaches and streams (Simon 2006). Measured unit values of fine sediment erosion rates ranged from 12.2 $m^3 \cdot y^{-1} \cdot km^{-1}$ for Blackwood Creek to 0.002 $m^3 \cdot y^{-1} \cdot km^{-1}$ for Logan House Creek (Simon 2006). Based on this empirical relationship, the Tahoe Watershed Model (Tetra Tech 2007) predicted that the contribution of stream channel erosion to total sediment loading from all sources was 19 percent, although the contribution of stream channel erosion to the number of fine sediment particles <16 µm in diameter (the pollutant of concern for water clarity) is currently estimated to be <5 percent of that from all sources (see "Lake Tahoe Water Clarity" section).

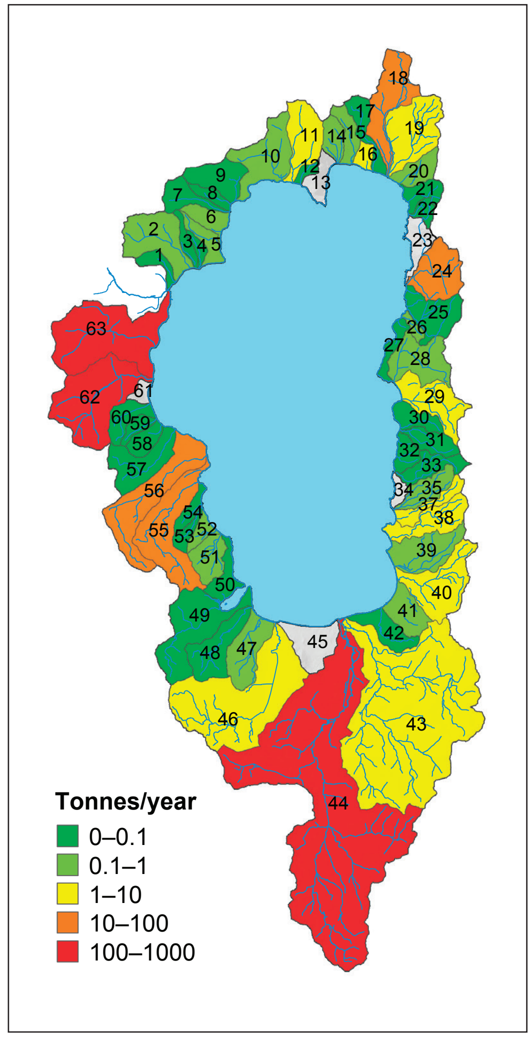


Figure 4.7—Fine-sediment loadings from streambank erosion (from Simon 2006).

Knowledge Gaps

The following discussion focuses on uncertainties and research needs associated with estimates of fine-sediment loadings from streambanks.

Stream channel cross sections—

- Estimates of sediment (<63 µm) loadings from streambanks are based on limited time-series cross-section surveys from a handful of streams and numerical simulations of three streams that were then extrapolated basin-wide based on observations of the extent of bank erosion at about 300 sites across the watershed. Although these data represent good estimates based on available data, additional time series and site observation data could reduce levels of uncertainty.

Fine sediment sources and channel processes—

- The influence that urbanization in the Tahoe basin has on runoff and stream hydrology and ultimately stream channel erosion is not fully understood.
- Uncertainties exist in the ability to quantify rates and volumes of bank erosion on stream segment and river-wide scales under historical, current, and future conditions. For example, measurements of flood-plain deposition rates in downstream areas of the Upper Truckee River and other streams will aid in determining the fate of fine sediment eroded from upstream areas.
- A better understanding of flood-plain processes, channel overbanking frequency and dynamics, and other geomorphic processes is needed to help guide restoration planning.
- The legacy impacts upon current rates of stream channel erosion and sediment transport from major watershed disturbance that occurred during the timber clearcut in the late 1800s are not well understood.

Model improvement—

- The CONCEPTS model needs to be further calibrated (for specific conditions at Lake Tahoe) and validated to demonstrate its effectiveness in providing useful guidance for design-level planning at the project scale.
- Improved erosion routines in the upland flow and sediment transport models are needed as they serve as the upstream boundary condition for running the CONCEPTS channel-evolution model and predicting upland contributions.

Research Needs

Stream channel cross-sections—

- Establish, monument, and maintain additional cross sections for annual surveys. Collect field observations along stream courses, particularly in previously unsampled streams. Ideally, these surveys would include determination of the particle-size distribution of stream channel material susceptible to erosion.

Fine sediment sources and channel processes—

- Separate natural from anthropogenic stream channel erosion loading to distinguish between baseline loads and treatable loads.
- Conduct sediment-tracking research using stable radionuclides or other elements to differentiate between the percentage of sediment and fine particles emanating from upland and channel sources.

- Complete additional modeling of streams that are known to contribute substantial quantities of sediment from the channel margin using CONCEPTS to test alternative strategies for erosion control and to predict the amount of load reductions that could be obtained by these strategies.
- Determine the influence of the Comstock logging activities on current stream channel erosion; determine how (if) legacy impacts from the Comstock logging will affect the efficacy of future channel restoration work.
- Establish an understanding of recent (historical and late Holocene) streambank sediment sources, sizes, and relative rates of erosion.
- Link CONCEPTS modeling flood-plain water quality modeling to estimate load removal associated with channel overflow.

Model improvement—

- Develop improved hydraulic routines, in 2- and 3-D to support better channel model (CONCEPTS) predictions of lateral migration, bank erosion, planform change, and slope adjustment.
- Fully integrate the CONCEPTS channel evolution model with the upland flow and sediment-transport models AnnAGNPS and LSPC.
- Test and validate estimates of the shear stress required to entrain upland materials and the associated erodibility coefficient used in the upland models. Ideally, this work would be completed on different soils and geologic units using in situ field-based measurements.
- Collect calibration/validation data regarding ground water, surface water, seasonal ice, and vegetation interactions, with regard to bank failures in selected reaches that have been or are being modeled using CONCEPTS.
- Collect field data regarding the in situ bank strength properties of stabilized or constructed bed/banks associated with recent stream restoration practice, such as excavated channels, placed riffles, or sod revetments.

Water Quality Treatment

Water quality treatment and source control measures are a key focus of management programs aimed at improving water quality in the Lake Tahoe basin. Although important research and monitoring has occurred in the past, future efforts will be most productive if they are hypothesis-driven to answer specific questions on the best methods for water quality treatment and source controls throughout the basin. Further, better integration of the research and monitoring results to date is recommended to address information needs at multiple spatial scales (e.g., at the project, watershed, and basinwide scales).

As with the other subthemes considered in this chapter, fine sediment and the nutrient forms of N and P are the primary pollutants of concern relative to water quality treatment and source control. Fine sediment and nutrients enter the lake from streams, atmospheric deposition, intervening areas, shoreline erosion, and by ground-water inflow (LRWQCB and NDEP 2008a, Reuter and Miller 2000, Reuter et al. 2003). Since 1970, several projects have been undertaken to reduce the quantity of sediment and nutrients entering the lake. Perhaps the most important project has been the pumping of treated effluent out of the Lake Tahoe basin. Additionally, the 1987 Clean Water Act Revision greatly affected transportation agencies by requiring more emphasis on wetland mitigation and stormwater management. Transportation agencies throughout the country began constructing wetlands and stormwater detention basins in response to provisions in the act. Numerous detention basins have been constructed in the Lake Tahoe basin (Fenske 1990, Reuter et al. 1992b). Constructing wetlands in or adjacent to stormwater detention basins has been shown to provide marked improvements in the quality of stormwater runoff (Martin 1986; Scherger and Davis 1982; Reuter et al. 1992a, 1992b). However, some potential exists for degradation of the ground-water quality beneath detention basins and associated wetlands (Church and Friesz 1993, Granato et al. 1995, K.B. Foster Civil Engineering Inc. 1989, 2ndNature 2006a).

Planning for a comprehensive water quality treatment plan for the Tahoe basin has taken a substantial step toward the completion of a pollutant reduction opportunity evaluation (LRWQCB and NDEP 2008b) as part of the Lake Tahoe TMDL. This analysis estimated potential pollutant load reductions and associated costs at a basinwide scale. It was the first comprehensive analysis of possible load reductions from the major source categories of urban runoff and ground water, atmospheric deposition, forested uplands, and stream channel erosion. This analysis was done in three steps including (1) an evaluation of potential pollutant controls applicable within the Tahoe basin, (2) a site-scale analysis that included an evaluation of treatable areas and the potential level of treatment within each, and (3) an extrapolation to the basinwide scale. The uncertainty analyses conducted for each of the major pollutant source categories in that report highlighted where assumptions were made and best professional judgment applied. Much of the research discussed in this section will help fill those types of knowledge gaps and advance the TMDL as a living water quality improvement plan for Lake Tahoe.

BMP Implementation, Operations, and Maintenance for Water Quality Treatment

Implementation of BMPs in the Lake Tahoe basin has generally focused on soil restoration projects and hydrologic controls (installation of basins, culverts, and surface runoff conveyance). The overall effectiveness of these strategies has not been well evaluated for water quality improvements. Although a few individual BMPs have been extensively monitored for performance in the Tahoe basin, these tend to be the exception (e.g., the compilation of published studies in 2ndNature 2006b, Reuter et al. 2001). There is not yet a clear understanding of what BMPs work in subalpine environments like the Tahoe basin. It is likely that continued implementation and management of water quality BMPs in the Tahoe basin will be necessary over the long term. Thus, a better understanding of effective BMP design, operation, and maintenance will be essential for sustained water quality improvements.

Effective BMPs for the protection and restoration of Lake Tahoe clarity will differ in some aspects from standard designs used in other parts of the country, largely owing to the unique climate characteristics in the Tahoe basin (e.g., rain and snow in winter, infrequent thunderstorms, and dry summers), as well as the fairly thin granitic soils, relatively low BMP influent concentrations, and very low desired BMP effluent concentrations. Thus, for Tahoe installations, it has been difficult to use with confidence the BMP design and effectiveness information from other parts of the country. Preliminary results from Tahoe-specific studies suggest, however, that in some cases, the overall effluent concentrations and efficiencies are similar to the national averages (Heyvaert et al. 2006b).

Most annual runoff into Lake Tahoe occurs from snowmelt and rain-on-snow events. These are typically due to large frontal storms that arrive as nominally uniform events around the Tahoe basin, where BMPs are usually designed to meet standards of hourly precipitation intensity (e.g., the 20-yr, 2.54-cm of precipitation in 1-hour storm event). In contrast, high-intensity thunderstorms typical of summer are much more variable in terms of spatial extent and intensity. A short-duration Tahoe summer thunderstorm of only 10 to 15 min can generate very high flows that scour online BMPs and exceed the first-flush capacity of offline BMPs. These summer thunderstorms are frequently a substantial source of sediment loading (Gunter 2005, Jones et al. 2004).

In the Tahoe basin, studies of BMP effectiveness have been largely confined to new or well-maintained projects. These studies may not capture the true range of performance for different types of BMPs or BMPs of different ages. Most treatment BMP designs in the Tahoe basin do not undergo comprehensive scientific or technical review by specialists. Common design problems, such as hydraulic short-circuiting, could be avoided if this review practice were implemented as a standard operating procedure.

Typical BMP evaluations can underestimate total particulate loads, especially the flux of very coarse material and debris that tends to fill basins and vaults. Capturing this information is important for developing maintenance programs. To address this issue, an alternative mass balance approach has been recommended, where feasible, for basins and vault evaluations (Heyvaert et al. 2005). This alternative approach substantially improves estimates of performance and life-cycle costs, particularly as related to maintenance requirements. To date, only limited data are available on the sustainability and life-cycle costs of BMPs. This is especially true for infiltration basins because of their high rates of failure caused by reduced infiltration capacity over time.

Detention basins are one of the most common BMPs in the Tahoe basin for removing sediments, nutrients, and other contaminants from urban and highway runoff. Although this type of BMP may abate surface-water loads, any infiltrated stormwater can contaminate shallow ground water and potentially increase the ground water gradient and flows into the lake. In addition, contaminants associated with urban runoff often include organic compounds and metals that are potentially toxic when consumed with drinking water. Processes that affect ground water contamination from stormwater have only just begun to be considered (e.g., Prudic et al. 2005, Thomas et al. 2004), but understanding these details is important because a substantial number of EIP projects are planned that will increase infiltration of urban runoff to comply with TMDL regulations.

Pollutant loads in Lake Tahoe are highly variable under the normal range of annual precipitation and runoff (Heyvaert et al. 2008). Therefore, accurate estimation of long-term benefits from various management strategies will depend upon simulations over the full range of climate conditions and would include phased implementation for improvements, coupled with the effects from variable runoff quantity and quality. The first step toward this approach has been made with development of the LSPC watershed model and the LCM, as part of phase 1 in the Lake Tahoe TMDL program (LRWQCB and NDEP 2008a, 2008b; Perez-Losada 2001; Riverson et al. 2005; Sahoo et al. 2007; Swift et al. 2006). Initial modeling results and monitoring data confirm, for example, that high runoff years are highly correlated with declines in lake water clarity. Better BMP designs, implementation, and maintenance will be needed to help reduce this effect.

Urban Source Control

Hydrologic management is typically one of the first steps in sediment source control for urban landscapes. By reducing runoff intensity and volume, the downstream hydrographs show lower peak flows that are spread over longer periods and generally have lower pollutant loads. Hydrologic management also is an effective form of erosion control; however, some level of soil restoration is often necessary in disturbed areas to remediate compaction, protect surfaces, and restore soil function (see "Key Soil Properties" section in chapter 5). Other forms of source control include structures or materials, such as retaining walls or rock and vegetation coverage of unstable roadcuts or slopes. Hydrologic management in urban areas will be especially important for controling soil erosion from erosional hot spots, areas that produce large sediment loads during stormwater runoff.

New Treatment Technologies and Enhanced BMP Designs

Standard types of BMPs may not adequately achieve the pollutant load reductions necessary for improving Lake Tahoe clarity. A combination of standard BMPs and new types of BMPs will likely be needed to achieve low pollutant effluent concentrations destined for Lake Tahoe. Thus, additional efforts have been made over the last few years to explore alternative approaches and technologies for stormwater treatment in the Tahoe basin. Various mechanical and chemical methods for purifying water are well known. However, they tend to be expensive, energy intensive, and are not well suited for dealing with large volumes of stormwater runoff. In addition, there are certain factors at Tahoe that constrain potential solutions for stormwater runoff quality, including (1) extremely low nutrient and sediment target concentrations and (2) cool subalpine air and water temperatures that limit biological productivity. In wetlands, for example, the nutrient uptake by macrophytes and emergent vegetation tends to be lowest in winter and spring, which are times of maximum storm runoff and snowmelt (Reuter et al. 1992a).

There are three broad areas of research on new BMP technologies that could be applicable to the Lake Tahoe basin. These include studies on (1) unit processes and treatment trains, (2) hybrid systems that provide chemical and mechanical augmentation of natural processes (e.g., co-precipitation of P with aeration and water pumping in constructed wetlands), and (3) novel ecological treatment systems (e.g., cultured periphyton, floating wetlands, submerged aquatic vegetation, clams and other filtering organisms, complex ecologies, and industrial food webs).

Coagulation is beginning to be more tested and applied for reducing stormwater turbidity (e.g., Harper et al. 1999). Laboratory and small-scale coagulations studies for the Tahoe basin have demonstrated that dissolved P and fine particles can be removed effectively with coagulation (e.g., Bachand et al. 2006a, 2006b; Caltrans 2006). Ultimately, the new treatment technologies required to achieve compliance with TMDL and water quality standards in the Tahoe basin may approach or be equivalent to technologies employed in the drinking water and wastewater treatment industries, including reverse osmosis, membrane filtration, flocculation, sedimentation, and filtration.

Phosphorus removal by adsorptive media is another BMP technique currently under investigation, in part because soils in the Tahoe basin have relatively low P adsorptive capacity. Although the use of natural or engineered media (including derivatives of calcium, aluminum, iron, or lanthanum) can greatly increase available adsorptive capacity, they also cause changes in pH and other chemical characteristics of the treated water that may be detrimental (Bachand et al. 2006a, 2006b; Caltrans 2006).

Existing BMP standards tend to result in designs that are not optimized for targeted pollutants in the Lake Tahoe basin. Most BMPs, for example, will not effectively remove fine particles and dissolved P from storm runoff when there is surface outflow through the systems (2ndNature 2006b, Strecker et al. 2005). Simply implementing current BMP designs, therefore, is not likely to meet the ultimate requirements for maintaining or improving lake clarity. Advancing BMP design standards at Tahoe will be important for achieving the TMDL and effluent standards.

Substantial efforts have been completed recently for enhancing BMP design in the Lake Tahoe basin. One such project is the Lake Tahoe Basin Stormwater BMP Evaluation and Feasibility Study (Strecker et al. 2005); another is the Pollutant Load Reduction Model (NHC 2009). These projects have assessed current design standards for BMPs in the Lake Tahoe basin, and have suggested potential refinements to BMP designs that would enhance performance. In addition, they have provided a draft methodology and associated spreadsheet tools for assessing options that maximize BMP effectiveness, both onsite and at the small watershed scale. Together, these projects have applied the latest BMP performance information from both the National BMP Database and from local Tahoe BMP performance studies, along with scientific knowledge on unit processes, to provide a reasonable evaluation of potential enhancements to BMP performance that could improve treatment for the pollutants of concern.

Knowledge Gaps

BMP implementation, operations and maintenance for water quality treatment—

A uniform definition that quantifies BMP effectiveness in treating fine sediment and dissolved fractions of nutrients on an event, seasonal, and annual basis is recommended. This definition would be based on performance studies in the Lake Tahoe basin given the low effluent standards and the primary pollutants of concern. Ultimately, a much better understanding of effective treatment technologies, including treatment train approaches and infiltration practices is recommended to achieve compliance with Lake Tahoe TMDL requirements, particularly in areas of high-density development.

The costs and components of oversight programs to ensure that BMPs are correctly monitored, maintained, or retrofitted to meet the fine particle and nutrient load reduction requirements have not been determined. Particular information needs include the long-term sustainability and life-cycle costs of BMPs, removal costs for particulate residuals, and disposal requirements for each type of BMP.

A better understanding of the interactions among source categories and BMP implementation strategies is needed for accurate model simulations. When appropriately calibrated and verified, these simulations would provide opportunities to investigate the effectiveness of potential management actions on achieving environmental thresholds as part of the TMDL Program. Validating the results from these simulations is recommended to achieve confidence in the predictions of the long-term effects on water quality and lake clarity.

New treatment technologies and enhanced BMP designs—

The potential effectiveness of modified or nonstandard BMP designs is under investigation, including coagulant-enhanced particle settling, filtration, biological treatment, and sorptive media. Anionic polyacrylamides show promise for turbidity treatment, but have not yet been studied for application in the Tahoe basin. Understanding and quantifying the toxicity effects of any potential chemical treatment is recommended before implementation in the Tahoe basin.

With adequate surface area and hydraulic retention time, wetlands can be very effective at removing N, P and sediment from urban runoff. However, conventional designs for treatment of wetlands and detention basins only make use of a relatively small subset of the potentially useful biological and ecological processes. In many wetland and aquatic systems, for example, a higher percentage of

P removal from the water column may occur via algae attached to plant stems and on surface sediments than through uptake by higher plants. Thus, for enhanced design opportunities, the treatment potential of other organisms and their combination in novel ecological systems should be investigated further in the Tahoe basin.

Research Needs

BMP implementation, operations and maintenance for water quality treatment—

- Improve BMP performance assessments based on standardized methods. It is recommended that these assessments focus on fine particles and nutrients and use our understanding of physical-chemical processes to improve the design of treatment systems through sound engineering principles.
- Although not considered research per se, establishment of a centralized database of Tahoe BMP information support of stormwater and BMP research is recommended. Ideally, this database would include data on BMP location, area, and land uses; the type of BMP installed, its capacity, installation date, inspection dates, and maintenance information; as well as water quality data, and monitoring records. The available data also could include BMP design criteria (hydraulic loading, residence time, width/depth ratio, aspect ratio, vegetation types), where the specified criteria are linked to predictable performance standards for specific pollutants of concern.
- Complete applied research to create better design guidance and specific BMP requirements for the Tahoe basin to achieve uniform treatment and pollutant reduction targets. This could lead to a design manual that would be used to enhance BMP selection and design criteria in the Tahoe basin. This includes a process of standardized scientific review for BMP implementation, operation, and maintenance. Design criteria could link directly to specific BMP functional characteristics and processes that improve performance based on integrated results from monitoring and modeling.
- Characterize the processes that influence nutrient transport from infiltration basins to shallow aquifers. This effort would include evaluating the removal (or addition) of pollutants during infiltration of stormwater into different underlying soils, as well as estimates of long-term seepage and pollutant loading at locations where ground water discharges into Lake Tahoe.

- Identify and characterize emerging pollutants of concern in terms of their removal by and effects on treatment BMPs.
- Conduct additional BMP monitoring to improve the prediction capabilities of models that are under development. Testing these models at a variety of field sites and scales for comparison to actual monitoring data will help validate results and inform design practices.

Urban source control—

- Conduct scientifically based effectiveness evaluations on different types of soil cover and erosion control materials, including longer term studies on soil restoration success and nutrient regimes.
- Develop appropriate metrics for evaluating the long-term success of urban source control projects in terms of their fine sediment particle and nutrient-retention characteristics.

New treatment technologies and enhanced BMP designs—

- Conduct replicated experiments to systematically assess the potential of new treatment technologies. A standardized, comparative approach will be needed to (1) predict and quantify performance; (2) understand the mechanisms of performance; (3) understand or identify ancillary effects, consequences, or benefits; (4) refine the logistics of application; and (5) understand inherent limitations.
- Conduct research on enhanced methods for capturing fine sediment in the 0.5 to 16 µm range, especially for BMPs that can remove substantial sediment loads from surface runoff.
- Evaluate the potential for engineered soil matrices that better adsorb nutrients, remove fine particles, and provide improved infiltration rates.
- Test anionic polyacrylamides in conjunction with other passive treatment technologies to determine their ability to reduce runoff turbidity and hence sediment loads.
- Determine the toxicity of stormwater and different treatment technologies before large-scale implementation of new technologies is authorized for the Tahoe basin.
- Determine what other stormwater pollutants could be treated by standard or enhanced BMPs. Examples of these pollutants include metals (i.e., cadmium, copper, and zinc), polyaromatic hydrocarbons, gasoline products (benzene, toluene, ethylbenzene, and xylenes and methyl tertiary butyl ether) and pesticides (pyrethroids).

- Develop a geographic information system (GIS)-based load reduction model to identify constituents and runoff volumes that could be most effectively addressed by different treatment methods, and to predict the results from different implementation strategies at various locations. It is possible, for example, that large regional advanced treatment systems would yield benefits from economies of scale and greater geographic flexibility compared to stormwater treatment applied through individual BMPs.
- Conduct comprehensive studies to quantify and weigh the risks, benefits, costs, and maintenance requirements associated with new types of BMPs that may be introduced into the basin.

Upland Watershed Function—Hydrology and Water Quality

More than 50 years of development in the Lake Tahoe basin has caused an increased flux of sediments and nutrients into the lake owing in part to soil disturbance and subsequent translocation. Road development and other forms of land disturbance, especially in areas of sloping topography, result in accelerated erosion and the accompanying loss of nutrient-containing topsoil. This is accompanied by the exposure of compacted, readily erodible decomposed granite, or andesitic volcanic subsoils, which are the dominant soil types in the Tahoe basin. Erosion and decreased infiltration rates in uplands are largely a result of soil disturbance by logging, grading, grazing, and related practices that result in loss of top layers of organic matter, established vegetation and nutrients, and subsequent soil compaction. The greater the disturbance in terms of soil impacts, the greater the erosion potential and loss of hydrologic function. As the physicochemical soil quality declines, vegetation growth is limited, soil stability decreases, and protective slope covers are lost that would otherwise minimize erosion. Efforts attempting to slow nutrient input to the lake have taken many forms, most of which focus on sediment source control including onsite retention.

Upland source control is critical for reestablishing hillslope hydrologic function with respect to soil moisture retention and percolation to ground water. Improved hydrologic function enhances plant cover conditions, habitat, flood peak attenuation, and can result in greater amounts of fine sediment particles remaining onsite. For example, using GIS assessment methods, Maholland (2002) evaluated the sediment sources and geomorphic conditions in the Squaw Creek watershed northwest of Lake Tahoe, a mixed granitic and volcanic soils environment. He found that forest road ski runs subject to hillslope rilling were the greatest sources of sediment in the watershed. Unfortunately, and despite years of work, little scientific information exists about the performance of road cut or hillslope erosion control measures employed in the Tahoe basin. However, there are numerous examples of anecdotal or visible failures in erosion control especially along road cut and ski run areas.

The nonurban landscape represents the largest land use in the Tahoe basin (about 90 percent). Although this land largely supports a forest biome, it is by no means unimpacted. The clearcut logging practices from the Comstock Era (1860 to 1890s) affected the composition of forest vegetation: populations of major tree species and forest structure never returned to pre-Comstock conditions (Barbour et al. 2002). Additionally, erosion hot spots are readily visible on the landscape. These areas of increased erosion occur at a variety of spatial scales ranging from the Ward and Blackwood Canyon Badlands (subwatershed scale) to landslide/avalanches (catchment scale) and from large to small gullies.

Although there is an enormous amount of literature related to erosion control in agricultural and relatively humid environments, there are few statistically validated field evaluations of the performance of revegetation/restoration type erosion control efforts in semiarid, subalpine environments. Information that is available is often limited to the "grey" literature or "white" papers from agencies, consultant reports, or professional societies. Although erosion control work is not new in the basin, documented results when available lack the scientific rigor needed to provide credible information for management decisions.

Selected examples of erosion studies that are relevant to the Tahoe basin include those of Fifield et al. (1988, 1989), Fifield and Malnor (1990), and Fifield (1992a,1992b) in western Colorado. In these studies, they evaluated the need for irrigation and runoff and erosion from plots "treated" with a variety of "natural" and geotextile covers on steep slopes. The "natural" treatments included hydroseeding, seed blankets, wood and paper hydromulches, straw, coconut, and jute materials. Generally, both runoff and sediment yields dramatically decreased as compared to bare soil conditions. Not surprisingly, the greatest sediment yield reductions were associated with the largest surface cover biomasses. What remains unknown are the long-term benefits of these erosion control strategies in the field, transferability to other locations, and what effects they have on infiltration rates and soil quality restoration. More recently, other efforts at assessing hydrologic effects of erosion control treatments at higher elevations or in nutrient-deficient soils have been reported. Montoro et al. (2000) described efforts to control erosion from anthropic soils on 40 percent slopes using 30-m^2 plots treated with vegetal mulch, hydroseeding with added humic acids and hydroseeding with vegetal mulch and humic acids. Runoff and erosion from natural rainfall events of 2 to 34 mm/h were significantly reduced from all treatments as a result of "protection against raindrop impact" and "general improvement in soil structure."

In the Tahoe basin, rainfall simulation studies have provided a means by which to standardize evaluation of erosion control measures, in a more controlled setting, through replicated rainfall events of the same intensity (or kinetic energy) on multiple plots enabling statistical evaluation of treatment effects on hydrologic parameters of interest. Grismer and Hogan (2004, 2005a, 2005b) reviewed available literature associated with erosion control measures in subalpine regions and applied rainfall simulation methods to assess runoff and erosion rates for disturbed granitic and volcanic bare soils in the Tahoe basin. The most fragile and easily impacted soils are of volcanic origin. Erosion rates of volcanic soils, and to some degree infiltration rates, are slope dependent. They also found that sediment yield (kilograms per hectare per millimeter runoff) from bare soils is exponentially related to slope after a minimum threshold slope is exceeded. Although rainfall simulation measured infiltration rates were similar in both volcanic and granitic soil types (30 to 60 mm/hr), sediment yields from granitic soils were several times smaller on average (from about 1 to 12 $g \bullet m^{-2} \bullet mm^{-1}$) than that from bare volcanic soils (from about 3 to 31 $g \bullet m^{-2} \bullet mm^{-1}$).

Granitic soil particle sizes were greater than that of volcanic soils in both bulk soil and runoff water samples. Runoff sediment concentrations and yields from sparsely covered volcanic and bare granitic soils could be correlated to slope. Sediment concentrations and yields from nearly bare volcanic soils exceeded those from granitic soils by an order of magnitude across slopes ranging from 30 to 70 percent. Similarly, granitic ski run soils produced nearly four times greater sediment concentration than adjacent undisturbed areas. Revegetation, or application of pine needle mulch covers to both soil types decreased sediment concentrations and yields by 30 to 50 percent. Incorporation of woodchips or soil rehabilitation that includes tillage, use of amendments (e.g., Biosol®,[8] compost) and mulch covers together with plant seeding resulted in little, or no, runoff or sediment yield from both soils. Although mulch and grass covers provide some protection to disturbed bare soils, they alone do not improve hydrologic function and may only minimally reduce erosion and runoff rates depending on the extent or depth of coverage (Grismer and Hogan 2004, 2005a, 2005b).

Repeated measurements of sediment concentrations and yields for 2 years following woodchip or soil rehabilitation treatments showed little or no runoff. Revegetation treatments involving use of only grasses to cover soils were largely

[8] The use of trade of firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of product service.

ineffective owing to sparse sustainable coverage (<35 percent) and inadequate infiltration rates. It was suggested that a possible goal of restoration-erosion control efforts in the basin could be the re-creation of "native"-like soil conditions. "Native" soils below forest canopies with about 10 cm of duff, litter, pine needle mulch, or other organic matter have very high infiltration rates (>75 mm/hr) when the surface is not hydrophobic. When the surface is hydrophobic, runoff commences almost immediately with little infiltration in the first 10 minutes; although the runoff yields negligible mineral sediment, it can contain high nutrient concentrations (Miller et al. 2005). Soil rehabilitation (woodchip or compost incorporation) combined with revegetation appears to provide erosion control, increased infiltration rates, and restoration of hydrologic function for at least 3 years, maybe more.

Knowledge Gaps

In comprehensive reviews of erosion control systems for hill slope stabilization, Sutherland (1998a, 1998b) noted that the "formative years" prior to about 1990 resulted in a mass of information that lacked scientifically credible, standardized data. He argued for standardized evaluation methods that have field applicability and greater emphasis on the study of surface, or near-surface processes controlling erosion. Perhaps better still for the Tahoe basin, would be a greater emphasis on scientifically credible studies on the restoration of soil quality adequate to support hill-slope vegetation.

Scientific information about erosion control and soil stabilization methods is critical to local agencies, planners, and property owners who want to know which methods achieve the greatest reductions in erosion for the least amount of money. Forest management efforts related to water quality restoration planning lack both process-based erosion models (with the expectation of the use of the WEPP model) and the basic soil property/hydraulic information necessary for plausible prediction of streamflows and sediment (TSS) and nutrient concentrations.

Understanding the relationship between mineral fraction particle sizes and fine sediment and nutrient transport is crucial for the design of effective sediment traps/basins. For example, fine particle sizes (<16 µm) settle out extremely slowly and are not trapped in many cases, whereas larger particles of lesser water quality impacts can be trapped in smaller BMPs (e.g., drainage sediment cans or small detention basins). Further, contrary to prevailing thought, vegetation cover alone (e.g., grasses with 30 to 60 percent cover that look good) may have little effect on reducing erosion rates from disturbed soils. Scientists and managers in the Tahoe basin have posed numerous relevant questions, including:

- What types of covers are effective for erosion control?
- How effective are various types of cover relative to the level of effort required for implementation?
- Can effective covers be realistically deployed over large areas?
- What are the maintenance requirements both short and long term?
- How do soil stabilization and erosion control approaches compare when applied at the project, watershed, and basinwide scales?
- Is artificial replenishment necessary when using mulch covers?
- Can soil be "rehabilitated" such that natural processes prevail (e.g., functional soil nutrient and microbial communities, growth of plants that leave a functioning litter layer)?

Research Needs

Erosion and pollutant loading—

- Study runoff particle-size distributions, sediment and nutrient loading from the undeveloped, yet disturbed forest landscape. This includes, but is not limited to (1) the mechanisms at play in the erosional hot spots (at the full spectrum of spatial scales at which this erosion occurs), (2) estimates of pollutant concentrations and loading from forest land and the hot spots, (3) the transport of nutrients and sediments from the forest floor to receiving water bodies that are tributary to Lake Tahoe, (4) the ability to better incorporate these processes into management models, and (5) an understanding of potential load reduction strategies for these pollutant sources.
- Determine the impact of existing and legacy roads, trails (e.g., hiking or biking), and other areas of the forest that have been disturbed to accommodate transportation (including recreation), vis-à-vis hydrology (including baseflow) and sediment/nutrient generation.
- Develop monitoring protocols to identify restoration methods that are the most effective in controlling runoff of fine particles and nutrients. These protocols also would provide data for the development of descriptive relationships between nutrients and particle size (for different soil types including granitic and volcanic).
- Quantify the particle size distribution in runoff from steep disturbed slopes for both granitic and volcanic soils.
- Better characterize the possible effects of extreme hydrologic events and runoff from large tracts of disturbed land on erosion, sediment transport, and nutrient loading, given the risk of wildfire, avalanches/landslides, and other potential natural hazards in the mountainous terrain of the Tahoe basin, as well as future climate change.

- Quantify snowmelt-derived erosion across the basin, including monitoring and characterization of snowmelt-induced erosion rates from the different disturbed soils.
- Define the continuum, or threshold relationship between organic matter content of soil at Lake Tahoe and sediment yield (erodibility). Based on a better understanding of the nature of this relationship, there could be tremendous potential to develop a rapid assessment of potential erodibility based on litter layer thickness or percentage of organic matter in the surface soils.
- Develop process-based erosion models applicable to the basin under rainfall and snowmelt conditions—functional at scales ranging from the project scale to the entire basin—to help inform and guide management decisions related to watershed restoration.
- Quantify nutrient concentrations in shallow interflow on hill slopes under a variety of hydrologic and cover conditions. Subsurface flow in the top 20 to 30 cm of soil on the hill slope can be a major flow factor; however, it is not adequately considered in many erosion models. In the Tahoe basin, research shows significant shallow subsurface flow that essentially filters the "runoff" resulting in negligible sediment yields, but potentially substantial loads of dissolved nutrients.

Processes related to soil rehabilitation—

- Determine what soil shear strengths are associated with rehabilitated soils and how they are affected by vegetative succession.
- Determine how soil rehabilitation affects soil aggregate stability, what aggregate stability occurs in “native” soils, and what aggregate stability value should be achieved in restoration projects.
- Study hydrophobicity of “native” soils to determine the extent of this condition, how rapidly it breaks down in summer storms, and whether “native” soils are a source or a sink of N or P.

Restoration effectiveness—

- Determine the ecologic and economic feasibility of treating erosion hot spots in the forest landscape. A better understanding of the occurrence of natural versus anthropogenic erosion hot spots is needed to assist managers in making decisions on implementation strategies.
- Determine which restoration methods will provide the greatest return in terms of hydrologic function per effort required, followed by how long, or if, the restoration method will last and if it is sustainable or self-sustaining.

- Determine whether successful soil restoration will result in permanent establishment of vegetation and "native"-like soil conditions in the sense that little, if any runoff or erosion is encountered. What microbial communities are involved?
- Determine restoration costs (per unit area) and quantified benefit in terms of erosion control and hydrologic function.
- Apply rainfall simulators with soil and runoff measurements to standardized evaluation of the variety of restoration techniques currently available to restore soil function.

Water Quality and Forest Biomass Management Practices

Forest biomass management practices can affect surface water and ground-water quality. As described below, although some initial research has been done to address this issue, a more complete program is needed. This is especially important in the Tahoe basin where forest fuel accumulation is high, biomass reduction programs are a high priority, and water quality protection standards are also high.

Fire Suppression

Fire suppression in forests of the Western United States throughout most of the 20th century has resulted in extremely high fuel loads, reduced tree growth, increased disease and insect infestation, and increased risk of destructive wildfires (Bonnicksen 2007, Covington and Sackett 1984, Parsons and DeBenedetti 1979). In much of the eastern Sierra Nevada region, including Lake Tahoe and vicinity, these long-term impacts have been exemplified by a decline in forest health owing to the buildup of high tree densities and heavy understory, extensive ladder fuels, which provide vertical continuity between surface fuels and crown fuels, downed timber fuels, and deep organic layers on the forest floor (Johnson et al. 1997, Miller et al. 2006).

A common belief throughout the Tahoe basin and Sierra Nevada is that forests long protected by fire suppression contribute little in the way of water quality degradation via natural nutrient discharge, because nutrient uptake and interception are thought to be maximized by the thick vegetative understory (Reuter and Miller 2000). Recent research, however, has identified the presence of high concentrations of biologically available N (ammonium nitrogen [NH_4^+-N], nitrate nitrogen [NO_3-N]) and P (phosphate phosphorus [PO_4^{3-}-P]) in coniferous forest overland flow (Miller et al. 2005). This suggests that these nutrients may be derived from the heavy accumulations of overlying forest floor surface organic layers (O horizons) and that there has been little biological uptake, leaching, or direct contact with the mineral soil where strong retention of NH_4^+-N and PO_4^{3-}-P would be expected. As a potential source of biologically available N and P, transport of these nutrients from terrestrial to aquatic habitats in the Lake Tahoe basin may therefore contribute to the already deteriorating clarity of the lake (Loupe et al. 2007).

Wildfire

The buildup of heavy understory fuels (~93 200 kg/ha of biomass) also has increased the potential for catastrophic wildfires in the Tahoe basin. It is well known that wildfire affects the various nutrient pools available for waterborne transport (Baird et al. 1999, Blank and Zamudio 1998, Johnson et al. 2004, Murphy et al. 2006b, Neary et al. 1999, Smith and Adams 1991). For example, wildfire typically results in large gaseous losses of system N owing to volatilization, but may often cause increases in soil mineral N owing to heat-induced degeneration of soil organic N (Murphy et al. 2006b, Neary et al. 1999). Conversely, wildfire effects on inorganic P are far more variable with some studies showing increases (Hauer and Spencer 1998, Saa et al. 1993) and others showing decreases (Carreira et al. 1996, Ketterings and Bighamm 2000) in available P depending upon fire intensity.

Wildfire has been found to increase the immediate mobilization of labile (readily available) nutrients. Murphy et al. (2006b) reported no significant differences in nutrient leaching prior to burning, but during the first winter following a wildfire, soil solution concentrations of ammonium, nitrate, phosphate, and sulfate were significantly elevated in the burn area. In addition, elevated concentrations of inorganic N and P also were found in surface runoff from the Gondola burn area above Stateline Nevada (Miller et al. 2006). The effect of wildfire was to increase the frequency and magnitude of elevated nutrient discharge concentrations during the first wet season following the wildfire event. At least some of this labile N and P may well have made it offsite during precipitation or snowmelt runoff, thus enhancing the nutrient loading of adjacent tributaries[9] and their discharge into Lake Tahoe.

Immediately following the 2007 Angora Fire that burned nearly 1255 ha in the Upper Truckee River watershed, the USDA Forest Service Burn Area Emergency Response team (USFS 2007) reported an elevated erosion potential of approximately 22 to 76 tonnes of sediment per hectare and that ash and sediment delivery

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[9] Allander, K. 2008. Personal communication. Hydrologist, U.S. Geological Survey, 2730 N Deer Run Rd., Carson City, NV 89701.

to Angora Creek, the Upper Truckee River, and ultimately Lake Tahoe could be high resulting in unacceptable water quality conditions. Monitoring is ongoing, however, loading was reduced in Water Year 2008 due to very low precipitation.

Prescribed Fire

Prescribed fire has become a popular management strategy in the Sierra Nevada for the removal of undesirable vegetation and heavy fuel loads (Neary et al. 1999, Reuter and Miller 2000, Rowntree 1998, Schoch and Binkley 1986). Controlled burning can remove large proportions of understory vegetation, litter layers, and larger surface fuels with minimal effects on the dominant tree vegetation. The treatments are generally mosaic in character and of much lower burn intensity than wildfires. Although carbon (C), N, and sulfur (S) remain susceptible to volatilization at lower burn temperatures, other elements such as P require higher burn temperatures to volatilize. Thus, substantial system losses of nutrients as a result of prescribed burning are generally the result of offsite particulate transport from ash convection, and waterflow runoff and erosion (Caldwell et al. 2002, Loupe 2005, Murphy et al. 2006a, Riason et al. 1985) rather than volitilization.

Whereas wildfire has been shown to cause a dramatic increase in labile nutrient mobilization (Johnson et al. 2004, Miller et al. 2006, Murphy et al. 2006b), this effect has not been identified for prescribed fires. Murphy et al. (2006a) found no significant increases in the leaching of ammonium, nitrate, phosphate, or sulfate following a prescribed Sierran burn on volcanic soils. Neither resin nor ceramic cup lysimeter data showed any effects of burning on soil solution leaching. Although Chorover et al. (1994) found increases in soil solution and streamwater ammonium and nitrate following a prescribed fire on granitic soils at a western Sierrian site, Stevens et al. (2005) reported that prescribed fire in the Lake Tahoe basin had no effect on soluble reactive phosphate and only minimal effects on nitrate in streamwaters. In support of this latter finding, Loupe (2005) found controlled burning to result in a net decrease of inorganic N and P concentrations in surface runoff at a site near north Lake Tahoe. On this basis, Murphy et al. (2006a) concluded the most ecologically significant effects of prescribed fire on nutrient status to be the substantial loss of N to the atmosphere from forest floor combustion.

Mechanical Treatment

Mechanical treatment is a forest management approach that includes techniques such as tree removal, chipping, mastication, grinding, etc. to control slash and other undesirable biomass. Reduced biomass accumulations improve forest health while decreasing the threat of wildfire (Klemmedson et al. 1985). Such treatments may temporarily increase litter mass from slash inputs; however, in the long term, mechanical treatment can (1) reduce new litter input by decreasing the number of young pole-sized trees, and (2) modify nutrient cycles through changes in plant uptake, substrate availability, infiltration ability, and soil temperature and moisture conditions (Parfitt et al. 2001, Smethurst and Nambiar 1990).

Although biomass reduction by fire has been shown to impact the nutrient pools available for waterborne transport (Baird et al. 1999, Blank and Zamudio 1998, Johnson et al. 2004, Miller et al. 2006, Murphy et al. 2006a, Neary et al. 1999, Smith and Adams 1991), much less is known regarding the effects of mechanical harvest. Hatchett et al. (2006a, 2006b) conducted a study on the west shore of Lake Tahoe to determine if heavy mastication equipment used for stand-density reduction would increase soil compaction, decrease infiltration, and thereby increase runoff and erosion: processes which would also be expected to increase nutrient and fine sediment discharge to adjacent tributaries. Data from cone penetrometer measurements indicated that the use of heavy mastication equipment did not cause significant compaction, regardless of the distance from the machine tracks. Furthermore, artificial rainfall applications showed erosion and runoff rates to be more dependent on soil origin, regardless of surface treatment (Hatchett et al. 2006).

Cut-to-length harvest/chipping mastication treatment in the absence of fire results in lower runoff concentrations of inorganic N, P, and S (Loupe 2005). Interactions between mechanical treatment and prescribed fire were more varied; however, the overall findings indicated that both prescribed fire and mechanical harvest management strategies have the potential to improve long-term water quality by reducing the nutrient content in surface runoff. Although prescribed fires have been typically reported to not result in P volatilization from organic combustion because of lower burn temperatures than wildfires, Murphy et al. (2006a) found the opposite to occur within the slash mats of the cut-to-length treatments, which would be expected to burn at higher temperatures. Surprisingly, some increases in soil C and N in both the slash mats of cut-to-length and skid trails of whole tree harvest were identified. Overall, however, the study by Murphy et al. (2006a) suggested the higher fuel loadings in the slash mats did not cause deleterious effects to either soils or water quality.

The USFS has been monitoring the implementation and effectiveness of timber harvest BMPs to protect soils and water quality using the USFS California Region BMPs evaluation program protocols developed in cooperation with the California State Water Quality Control Board. This qualitative assessment has found that since 1992, Timber Harvest BMPs on the Lake Tahoe Basin Management Unit (LTBMU) have been effectively implemented about 90 percent of the time in terms of soil erosion; however, this assessment did not include an assessment of nutrient concentrations.

Knowledge Gaps

Fire suppression—

Comprehensive fire suppression has caused a shift from more frequent low-intensity fires, which were presumably prevalent prior to European settlement, to catastrophic, stand-replacing wildfires. Accurate assessments of the true nutrient status of pre-European pristine forest conditions are unavailable. Hence, the water quality effects of this paradigm shift are difficult to evaluate primarily because of the lack of prewildfire samples and suitable historical controls for assessing specific wildfire effects.

Comprehensive fire suppression has caused a decline in forest health, in part resulting in a buildup of excess organic debris that may now be an important source of biologically available N and P in naturally derived surface runoff. Litter mass is typically considered to be a nutrient sink; however, the equilibrium has apparently shifted such that the amount of nutrient mineralization within the excessive biomass has increased causing the release of large amounts of available nutrients into solutions passing through it—albeit the extent of which has not been fully quantified. Although the magnitude remains largely unknown, it now appears that overland flow from the forest may be an important source of dissolved nutrients discharged to nearby streams and lakes.

Wildfire—

Wildfire clearly has the potential to affect surface runoff water quality through enhanced mobilization of labile nutrients (likely through temperature-induced mineralization) and subsequent increased discharge concentrations. Whether or not these newly mobilized nutrients actually make it offsite and into adjacent tributaries and Lake Tahoe during precipitation or snowmelt runoff is unknown. The frequency and magnitude of such surface discharges cannot be quantified at this time because we have no means of determining the flow volume on an areawide basis. The long-term effects of wildfire on runoff water quality are unknown but may ultimately result in a decrease in discharge nutrient concentrations over time owing to the dramatic reduction of heavy surface deposits of decomposing organic litter.

Areas affected by wildfire are frequently prone to flooding, landslides, and debris and sediment flows as a result of increased postfire erosion owing to lack of vegetation cover, and fire-induced subsurface hydrophobic layers that can increase the mass wasting potential of overlying wettable soil. With the exception of a very recent study (Carroll 2006), the degree and extent of fire-facilitated watershed erosion and accompanying nutrient discharge following the first major postwildfire precipitation event remains largely unknown throughout the Tahoe basin. Although it appears that the impact of a single erosion event following a wildfire may be at least an order of magnitude greater than the expected average annual erosion based on a 1,000-year projection, more accurate quantification of the specific source area is paramount to understanding the actual scale of erosion and potential nutrient discharge. In the case of the USFS-recommended water-quality-related BMPs following the Angora Fire, the primary focus was to reduce erosion and retain as much of the ash and disturbed soil onsite as possible. More research is needed to determine to what extent postwildfire BMPs can be designed to address nutrient mobilization.

Prescribed fire—

There is considerable information on the immediate effects of prescribed fire on biomass reduction; however, there is much less information on both the short- and long-term impacts on site nutrient status and potential discharge water quality. The effect of prescribed fire on residual nutrient mobilization appears to be far less than that associated with wildfire, but the availability of comparative studies is limited. The few studies that do exist suggest prescribed fire may have negative impacts on soil fertility and site productivity because of N losses (and in some instances P), and therefore enhanced potential for improved surface runoff water quality. The full extent to which prescribed fire plays a role in affecting soil properties that may influence infiltration, percolation, surface runoff, and ground-water discharge also is largely unknown.

Mechanical treatment—

Mechanical biomass reduction is an alternative management strategy to offset the potential for catastrophic wildfire and to improve forest health. The overall environmental costs/benefits of treating forests with mechanical harvesters/masticators have not been adequately characterized. Specifically, the impacts of new-technology mechanical harvesters and masticators on traditional soil and vegetative properties (e.g., compaction, infiltration ability, recovery, nutrient cycling) that can influence watershed erosion and surface runoff nutrient discharge have not been well characterized. Although short-term impacts in this regard appear to be minimal, impacts 1 to 3 years following treatment are uncertain and could be quite different.

The LSPC model and cumulative watershed effects analysis (using WEPP modeling) currently being conducted by the USFS is utilizing equivalent roaded acres (ERAs) coefficients developed by the USFS to estimate the area impacted by various vegetation management practices (i.e., compacted/disturbed surfaces). The ERA coefficients are based on the professional judgment of Forest Service hydrologists, but they have never been verified by systematic field testing. Although regulatory approaches currently limit or prohibit the use of mechanical treatment methods within Tahoe basin stream environment zones (SEZs), the technology has vastly changed since these regulatory approaches were established. New research is recommended to determine whether or not innovative low-impact mechanical treatment technologies can be operated within some areas designated as SEZs without causing significant impact to soil/hydrologic function.

Research Needs

Fire suppression—

- Further investigate soil and nutrient cycling parameters in pristine forested areas of the Sierra Nevada wherever possible to better establish treatment "control" scenarios; albeit the effects of fire suppression will be present to some extent.
- More fully quantify current nutrient contributions from the now thick O-horizon deposits throughout basin subwatersheds:
    - Better delineate the distribution and thickness of O-horizon deposits throughout the basin.
    - Quantify the potential contributions of inorganic N and P in kilograms per unit mass of dry matter; kilograms per unit area, and potential flux in kilograms per hectare per year.
    - Determine the amounts of inorganic N and P contained in surface runoff that discharge into adjacent wetlands, tributaries, and ultimately Lake Tahoe.
- Stronger quantification of the true functionality of intervening wetlands and riparian areas in terms of N and P source/sink interactions. For example, can agencies effectively mitigate increased upland overland flow discharges of N and P using existing SEZs?
- Research is needed to identify pertinent restoration strategies that, to the extent possible, will allow us to mimic historical conditions and functionality.
- A quantitative comparison of water quality effects of wildfire, prescribed fire, and mechanical treatment is needed. This comparison will involve compiling the limited data that are available and collecting new data where needed to evaluate the effects of these three scenarios within watersheds having similar hydrologic and soil characteristics.

Wildfire—

- Systematically study the effects of wildfire on nutrient and fine sediment status whenever possible where suitable adjacent control sites exist and especially in cases where, by happenstance, prefire data may be available. Further quantify and develop a better means of predicting short- and long-term changes in the amount of biologically available nutrients and fine sediment discharged from upper watersheds as a result of wildfire and during recovery.
- Apply spatial analysis models for balancing waterflow and nutrient budget parameters at the watershed scale to better assess the linkage between overland flow nutrient transport and discharge water quality as affected by catastrophic events such as wildfire and mass wasting.
- Evaluate the effectiveness of emergency treatments, typically applied to a burned landscape to control erosion, sediment/ash transport, and nutrient mobilization.

Prescribed fire—

- More information is needed on both the short- and long-term effects of regular prescribed fire and cut-to-length harvest fires on soil and water nutrient status to determine the most beneficial and most ecosystem "friendly" return interval.
- Implement a long-term assessment to quantify the relationship between regular reductions in litter-fall biomass accumulation, and the N and P content in overland flow runoff and discharge water quality at the watershed scale.
- Determine the impact of burn frequency on soil and vegetative properties that influence infiltration, percolation, surface runoff, and ground-water discharge.

Mechanical treatment—

- More fully investigate the short- and long-term impacts of various mechanical treatments (e.g., cut-to-length, whole tree, or mastication) for fuels reduction on soil cover, bulk density, infiltration capacity (as measured by K_{sat}), site recovery, nutrient cycling, and surface runoff water quality. Better characterization of the impacts of new-technology mechanical harvesters and masticators and their influence on watershed erosion, surface runoff, and nutrient and fine sediment discharge is recommended. Currently, this type of information is very limited. Further-more, it is recommended that this research provide information that can be extended throughout the basin to account for the very large spatial area that will be affected by mechanical treatment and the extremely large volume of biomass that will be removed.

- Further quantify residual and altered soil moisture status, soil cover, bulk density, and infiltration capacity to determine under what conditions innovative harvest technology can be safely applied within upland areas as well as those designated as SEZ using the existing SEZ indicators.

Both of the above research needs would benefit from demonstration projects and case studies that incorporate the different soil types and environments within the Lake Tahoe watershed.

Drinking Water Protection

Waters within the Lake Tahoe basin provide the drinking water supply for nearly a half million people living in the Tahoe-Truckee-Reno region, and over 50 million annual visitors to the region. In the Tahoe basin alone there are approximately 90 water companies, utility districts, independent domestic suppliers, and private suppliers.

These water purveyors draw from both ground- and surface-water supplies. The federal Safe Drinking Water Act (SDWA) and the Clean Water Act together provide the umbrella of protections that the U.S. Environmental Protection Agency (US EPA) uses to govern the protection of drinking water supply. The SDWA emphasizes the use of comprehensive watershed protection as an important means of protecting drinking water.

The Lake Tahoe basin is a source of high-quality drinking water. However, despite Tahoe's exemplary water supply, water purveyors and the state's health protection agencies continuously seek ways to improve public protection against exposure to toxic and microbial contamination. Drinking water protection efforts typically focus on inhibiting the entry of potential toxic or pathogenic pollutants to the water supply, and on eliminating the potentially toxic byproducts of disinfection processes.

Drinking water protection is crucial to human life and health. The U.S. EPA's Science Advisory Board (US EPA 1997 states:

> Exposure to microbial contaminants such as bacteria, viruses, and protozoa (e.g., *Giardia lamblia* and *Cryptosporidium*) is likely the greatest remaining health risk management challenge for drinking-water suppliers. Acute health effects from exposure to microbial pathogens are documented, and associated illness can range from mild to moderate cases lasting only a few days to more severe infections that can last several weeks and may result in death for those with weakened immune systems.

Research needs pertaining to drinking water protection focus on answering questions about the presence and proliferation of microbial contaminants and aim to inform managers in developing a watershed-protection approach to drinking water protection.

"From a watershed perspective, any practice that reduces runoff and erosion will reduce the transport of pathogen directly to surface water" (WSSI 2000). In this regard, efforts in the Tahoe basin to reduce runoff and erosion make a very substantial contribution to the overall efforts to protect drinking water.

Although sediment-reduction efforts in the Tahoe basin benefit drinking water, opportunities to be more effective in the protection of drinking water are often overlooked. Improving knowledge of drinking water issues and including these issues in basin management discussions is essential to the environmental, economic, and social health of all who rely on the Tahoe basin as a source of drinking water.

The SDWA amendment (PL 104-82) includes requirements that contributing areas for drinking water supplies be delineated and that potential sources of contamination be identified within the delineated areas (US EPA 1997). This can be accomplished by watershed management programs, which comprise individual practices to manage various types and magnitudes of contaminant sources within the hydrologic boundaries of a watershed (Walker et al. 1998).

Knowledge Gaps

The SDWA directs attention to three activities for the protection of drinking/source water: (1) characterize watershed hydrology and land ownership, (2) identify watershed characteristics and activities that may adversely affect source water quality, and (3) monitor the occurrence of activities that may adversely affect source water quality. Research is necessary at several levels to inform the development of a Tahoe-specific watershed management program comprising the most effective practices for managing drinking water contaminant sources.

Some of the key uncertainties regarding drinking water protection in the Tahoe basin include:

- The transport of pathogenic organisms (virus, bacteria, protozoa) in waterways and in Lake Tahoe.
- Pathogen viability.
- Animal waste and its effects on water quality.
- The role of natural and other bacteria in altering water quality through chemical and biological interactions.

- The need for drinking water protection to include toxic substance control.
- The ability to predict pollutant dispersal of particulates, colloidal particles, and pathogenic organisms.
- Bio-fouling of treatment infrastructure.

Research Needs

- Investigate methods of stormwater management/treatment effectiveness in limiting conveyance of fine sediments (and accompanying pathogens) into drinking water supplies.
- Determine the risk of contamination from specific activities such as stormwater drainage, domestic animals, wildlife and human sources, in proximity to surface water intakes and wellheads. Characterize these potential sources in terms of the risk that they present to drinking water supply relative to their ability to perpetuate, preserve, reintroduce, and activate *Giardia*, *Cryptosporidium*, *Escherichia coli*, and other pathogens in the environment.
- Build upon efforts to characterize land and water uses and their potential to contribute to microbiological and toxic contamination of the water supply (TRPA 2000).
- Utilize findings of the Lake Tahoe Basin Framework Study Wastewater Collection System Overflow/Release Reduction Evaluation (US ACE 2003) to hone in on potential "high risk" locations in the shore zone for wastewater contamination and investigate potential management practices that can minimize or eliminate risk. This also applies to toxic and nutrient contamination of drinking water sources.
- Build upon initial findings of the Detention Basin Treatment of Hydrocarbon Compounds in Urban Stormwater study (2ndNature 2006a) and Cattlemen's Basin Infiltration of Stormwater study (USGS 2004) to better understand the potential impacts of stormwater contamination on ground- and drinking-water sources.
- Develop pollutant dispersion models for particulates, colloids and pathogens in Lake Tahoe that focus on near-shore sources and water intake structures.
- Evaluate the potential applications of Tahoe TMDL modeling, tools and data to inform drinking water protection efforts.

Water Quality Modeling

Models are widely used in support of water quality and watershed research, planning, and resource management. In a diagnostic mode, they can be used to investigate cause-and-effect relationships by defining those critical factors that most determine how a water body or watershed responds to stressors and other ecological drivers. In a predictive mode, they can be used to forecast how a water body or watershed will most likely respond to management alternatives and environmental changes. They also provide an excellent framework from which we can assess our conceptual understanding of ecosystem function.

Rarely do scientists have the ability to assess ecological response to stressors based on ecosystem experimentation and large environmental manipulation studies. Although the combination of monitoring and process-based research allows scientists and resource managers to track environmental response over time and understand its causes, this approach is less than optimal because (1) it is slow; (2) researchers have less experimental or statistical control than in a laboratory or field experiment, so it can be difficult to detect a response from within the natural variability; (3) it is not possible to know a priori all the important variables to be measured, nor is it possible to measure them all; and (4) the ecosystem continues to change during the protracted period required to collect sufficient data. By describing the environment in quantitative or mathematical terms, models can provide invaluable management tools to help answer questions about stressors and ecosystem response and provide insight into current restoration efforts.

A mathematical model is an equation, or more commonly a series of equations that translates a conceptual understanding into quantitative terms (Rechow and Chapra 1983). Water-quality-related models are often broadly categorized as mechanistic and empirical. Mechanistic models attempt to mathematically define the actual ecosystem processes at play (e.g., in lake water quality models, these processes might include mixing and circulation, algal growth, food web dynamics, or nutrient cycling). Empirical models are based more on mathematical expressions of the relationships that appear in a set of data collected from the environment, and less on theoretical principles. For reference, the LCM (Perez-Losada 2001, Sahoo et al. 2007, Swift et al. 2006), used to evaluate Lake Tahoe’s response to nutrient and sediment loading, represents a mechanistic model and is based on linked algorithms describing lake processes. In contrast, Jassby et al. (2003) have developed an empirically based statistical time series model of Secchi depth variability based on actual field data measured over the historical period of record (>35 years).

Models can be useful tools for informing lake and watershed restoration. However, models have limitations. These include the ability to translate complex ecosystem processes into mathematical algorithms, the availability and quality of input data (both for initial conditions and boundary conditions), the technical capability of the model, and the expertise of the modeling team. "Blind" acceptance of model results is not recommended without careful evaluation of the models and modeling techniques. It is reasonable to expect that models and modeling approaches would require revision and updating as new data and new understanding of ecosystem processes become available through research and monitoring. At the same time, model results can frequently expose critical gaps in monitoring programs.

In the late-1990s, it was acknowledged that for the Tahoe basin, sufficient monitoring and research data were in place and the technical expertise available to begin development of a modeling "toolbox" for water quality/watershed management (Reuter et al. 1996). Furthermore, with the development of the EIP in 1997, it was understood that management models would be needed to help develop and evaluate alternative strategies.

Review of Tahoe Basin Resource Management Models

Selected models that are either currently in or under development/revision are briefly described in this section. Not all existing models are presented here, but this section does provide a relatively comprehensive overview of the models used to help evaluate and guide water quality restoration efforts in the Tahoe basin. Because the use of water quality and watershed models in the Tahoe basin is relatively recent, corresponding with development of the Lake Tahoe TMDL program, these models are currently at different stages of development.

Successful resource management models often are customized in one way or another to the specific conditions of the ecosystem under investigation. In some cases, an appropriate model does not exist and a new model would be recommended. These models are based on known principles of hydrology, earth science, water quality, biology, and chemistry, and are tailored for the ecosystem under consideration (e.g., LCM, LTAM, and PLRM). In other cases, algorithms and equations in an existing model are customized to reflect unique site-specific environmental conditions (e.g., LSPC as applied to the Tahoe basin). A third alternative is to populate existing models with site-specific input data to generate new results (e.g., CONCEPTS, WEPP, and Si3D). Each approach has pros and cons, and all three approaches have been used in the Tahoe basin.

Lake Clarity Model—

The University of California, Davis has been developing the Lake Tahoe LCM based on the extensive data collected on lake processes by the Tahoe Environmental Research Center (TERC) and others over the last 40 years. The LCM is a unique combination of submodels including a one-dimensional hydrodynamic model, an ecological model, a water quality model, and an optical model. This model was developed to specifically identify Lake Tahoe's response to pollutant loading and the pollutant reductions necessary for the protection of lake clarity (LRWQCB and NDEP 2008a, Sahoo et al. 2007).

Three-dimensional Lake Circulation Model (Si3D)—

The motion of water within Lake Tahoe determines to a large degree the fate of pollutants in the lake, and in the case of withdrawal of lake water for drinking purposes, the quality of that water. Si3D is a semi-implicit lake model that has been successfully used to describe the basin-scale motions within Lake Tahoe (Rueda et al. 2003). As originally developed, the model resolves the lake into 500- by 500-m horizontal grid cells each with a depth of 5 m. Advances in computer power, together with new techniques for embedded subgrids, allows the model to be used with horizontal grid resolution as small as 20 by 20 m and vertical grid scales of 1 m. Such resolution is compatible with processes in the near-shore zone, such as pathogen entrainment into drinking water intakes, pollutant tracking, and transport of invasive species. Coupling Si3D with water quality, ecological, and optical models of the LCM is also possible.

Watershed Model (LSPC)—

In direct support of Phase 1 of the Tahoe TMDL, Tetra Tech, Inc. developed the Lake Tahoe Watershed Model using the Loading Simulation Program in C++ (LSPC). The watershed modeling system includes algorithms for simulating hydrology, sediment, and water quality from over 20 land use types in 184 subwatersheds within the Tahoe basin. This model has been used to estimate the current pollutant loading to the lake from surface runoff and for the exploration of various scenarios during development of an Integrated Water Quality Management Strategy as part of Phase 2 of the Lake Tahoe TMDL.

Pollutant Load Reduction Model—

The Pollutant Load Reduction Model (PLRM) was developed for use in evaluating and comparing pollutant load reduction alternatives for storm water quality improvement projects in the Tahoe basin. It uses publicly available software with the US EPA Storm Water Management Model as its hydrologic engine. The PLRM provides predictions of storm water pollutant loads on an average annual basis for urbanized areas. The primary purpose of the PLRM is to assist project designers to select and justify a recommended storm water project alternative based on a quantitative comparison of pollutant loads and runoff volumes for project alternatives. Pollutant loads in storm water are highly variable, and notoriously difficult to predict with absolute accuracy at particular locations and times. The focus of the PLRM is to make use of best available Lake Tahoe storm water quality information to compare relative performance of alternatives over the long term. The recommended spatial scale of application for the PLRM is the typical Tahoe basin storm water quality improvement project scale (i.e., roughly 4.0 to 40.4 acres). The PLRM may eventually support broader objectives beyond prediction of the relative performance of storm water project alternatives (e.g., tracking TMDL progress, informing the Lake Clarity Crediting Program, and project prioritization). However, additional development, testing, and an institutional framework for supporting the PLRM are still needed.

Conservational Channel Evolution and Pollutant Transport System (CONCEPTS)—

CONCEPTS is a channel-evolution model developed by Langendoen (2000) with the USDA Agricultural Research Station. This deterministic numerical-simulation model is used to evaluate stream channel changes over time and simulate sediment loads from stream channel erosion. When used in concert with an upland watershed model (e.g., AnnAGNPS, LSPC, or WEPP), CONCEPTS can help in the quantification of the relative contributions of sediment from upland and channel sources. As part of Phase 1 of the Tahoe TMDL, Simon et al. (2003) used CONCEPTS to estimate fine sediment and total sediment loading to Lake Tahoe from General Creek, Ward Creek, and the Upper Truckee River. The importance of stream channel erosion to the loading of fine sediment was highlighted by Simon (2006) who found that stream channels provided about 25 percent of the annual sediment load for the <63 µm fraction.

Water Erosion Prediction Project (WEPP)—

The WEPP erosion model was developed by the USFS and is based on fundamentals of stochastic weather generation, infiltration theory, soil physics, plant science, hydraulics, and erosion mechanisms (Flanagan et al. 1995). The WEPP is a process-based model that can be used to estimate both temporal and spatial distributions of soil loss. This model accommodates variability in topography, surface roughness, soil properties, vegetation, and land use conditions on hillslopes. The WEPP is currently used by the US Forest Service-Lake Tahoe Basin Management Unit for evaluation of erosion control projects in the general forest.

Lake Tahoe Airshed Model (LTAM)—

The LTAM is a heuristic eulerian model designed to provide predictive capabilities for environmental management in the Tahoe basin, vis-à-vis, air quality and atmospheric deposition. A heuristic approach is one where the most appropriate solution to a problem, of several found by alternative methods, is selected at successive stages. Although it is not specifically a water quality or watershed model, it is well established that atmospheric deposition of nutrients and fine particles both substantially contribute to pollutant loading of Lake Tahoe (CARB 2006, Jassby et al. 1994, Reuter et al. 2003). Air pollution sources including automobiles, forest fires, and road dust can be put into the model. The model predicts pollutant transport and deposition across the basin and lake surface. The LTAM is an array of 1,248 individual 2.56-km^2 cells across the basin with a North-South range from Truckee to Echo Summit and an East-West range from Spooner Summit to Ward Peak. The LTAM is semiempirical in design, and incorporates available air quality measurements at Lake Tahoe, plus aspects of meteorological and aerometric theory. The model has two major immediate goals: (1) to predict the concentration of air quality pollutants in the Tahoe basin at spatially diverse locations where no data exist and (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).

Lake Tahoe Time Series Secchi Depth Model—

High year-to-year variability in lake conditions can obscure restoration actions and compliance with water quality standards. This is especially so when simple statistics are used to evaluate trends in long-term data. An overarching question for resource managers and scientists remains: How can we distinguish temporary improvements in lake clarity resulting from natural events from true and significant improvement as a result of restoration efforts? A time series model for Lake Tahoe Secchi depth was developed, incorporating a mechanistic understanding of interannual variability based on actual lake response over the historical data set (Jassby et al. 2003). The model focused on the summer when the lake is least transparent and most heavily used. The statistical model determined, with a very high degree of certainty, that interannual variability has been driven largely by precipitation differences. The model offers a tool for determining compliance with water quality standards when precipitation anomalies may persist for years, i.e., this model can help determine if the measured annual Secchi is simply climate-driven or represents a recovery of the lake based on restoration activities.

Knowledge Gaps

As discussed above, the development and application of predictive models to help guide resource management in the Tahoe basin is a relatively recent but important trend. Consequently, although managers and scientists agree that there is great potential in the application of these tools, it is acknowledged that information gaps exist resulting in varying levels of uncertainty.

Assuming that models will continue to be developed and used by researchers and resource managers in the Tahoe basin, it is vital that the models have as much scientific validity as possible. All research and other avenues of scientific inquiry that reduce the uncertainty in any aspect of these and other applicable models is encouraged.

While it is beyond the scope of this science plan to critically review the specific areas of uncertainty associated with each of the management models, there are general topics that apply to models collectively. As the modeling efforts continue and are expanded, additional areas of uncertainty are bound to arise.

Tahoe-specific numeric coefficients to support process-based modeling algorithms—

The important environmental driving forces captured in models are typically related to site-specific conditions. Each model uses a different set of modeling parameters, each with its own numeric characterization. Although literature coefficients are often used to support resource management models, they can add substantially to uncertainty. This is especially the case for the Tahoe basin, because of the unusual environmental conditions that exist (e.g., nutrient-poor granitic soils, mountainous topography, deep oligotrophic lake, and subalpine conditions) are not well represented in the literature. Research is needed to more accurately describe modeling algorithms and rate coefficients specific for the Tahoe basin.

Sufficient and appropriate model input data—

Models require reliable input data for initial conditions, boundary conditions, external sources (loads), and sinks (losses). Meteorological data is a critical category of input data for the water-quality-related models being used and developed for Lake Tahoe and the surrounding watershed. Meteorological conditions (e.g., temperature, precipitation, relative humidity, windspeed and direction, and solar radiation) are important forcing factors for erosion, hydrology, pollutant transport, lake currents, and vertical mixing. The mountainous terrain within the Tahoe basin is subject to both orographic effects and spatial variability in microclimatology. With climate change already acknowledged as an important factor in the Sierra Nevada, maintaining a temporally and spatially extensive real-time network of meteorological data (both lake and watershed stations) is critical.

Other types of model input data also need more up-to-date and complete input data sets. Examples include expanded atmospheric deposition and urban runoff data.

Validation of models using monitoring data from the Tahoe basin—
Model validation is a critical step in understanding uncertainty. During the validation phase of model development, the model run is compared to our actual understanding of the environment to determine if the model "got it right." If not, the model can be revised and improved. However, validation data do not always exist, or may be insufficient.

Model linkage—
By linking models, managers are better able to simulate environmental response on an ecosystem level. The importance of linked models is appreciated with the format of the Lake Tahoe TMDL (LRWQCB and NDEP 2008a, 2008b, 2008c). The initial step involved linking the output of sediment and nutrient loads from the watershed (LSPC) directly into the LCM. The TMDL Integrated Water Quality Management Strategy has recognized the need to link LSPC with CONCEPTS and LSPC with PLRM. Work is recommended to firmly establish these links and to investigate the feasibility of creating linkages between these and other models (e.g., LTAM and LCM).

Revision of existing models and development of new models—
Investigation of the applicability of existing or development of new models not yet under consideration for use in the Tahoe basin is recommended. For example, a model is needed to examine the growth response of near-shore periphyton to site-specific and basinwide nutrient loading, increasing water temperature, and invasive species.

Research Needs

- It is recommended that modelers work in close cooperation with scientists conducting field/laboratory research to ensure that the critical ecosystem drivers are incorporated into conceptual models and the mathematical expressions in predictive models.
- Collect a more comprehensive set of meteorological data to support models in the Tahoe basin. There is general agreement that current meteorological locations lack the spatial resolution to address the data input needs of models that operate from the project scale (hectares) to the entire watershed (about 800 km^2).

- Develop monitoring to support the goal of model validation as monitoring programs are redesigned or newly developed. This is especially important for the model(s) that will evaluate TMDL (load reduction) compliance.
- Revise models as new research addresses knowledge gaps and monitoring data are used to update input data and validate model output.
- It continues to be important to expand models to allow resource managers to evaluate the effectiveness of the EIP and TMDL compliance continue to be important. Examples of topics that would benefit from modeling include, but are not limited to, urban hydrology, pollutant loading from terrain impacts by fire, transport and reduction of fine particles (<16 µm) in natural environments and constructed BMPs, and linking near-shore and pelagic water quality and pollutant transport.
- Link key models such as the LCM, pollutant load reduction models, and the Tahoe Watershed Model (LSPC) to increase the benefit of these models to water quality managers.
- The PLRM model will be important to the TMDL Lake Clarity Crediting Program. Improvements to its calibration and validation will be critical to management.

Climate Change and Water Quality

There is now a strong consensus among climate scientists that (1) the Earth's atmosphere and oceans are warming; (2) the primary cause is the anthropogenic release of greenhouse gases; and (3) the impacts to natural systems and human societies over the next century will fall somewhere between serious and catastrophic (Oreskes 2004). Over the last hundred years (1906 to 2005), the global average near-surface temperature has increased 0.18 to 0.74 °C (IPCC 2007). Based on various climate models and greenhouse gas emission scenarios, the U.N. Intergovernmental Panel on Climate Change (IPCC 2007) projected a global average temperature increase of 1.4 to 6.4 °C by 2100. More locally, Dettinger (2005) found a central tendency for the distribution of many modeled temperature increases for California of about 3 °C by 2050 and 5 °C by 2100. At that rate, and with an average environmental adiabatic lapse rate of 2 °C per 305 m, the end-of-century temperature regime at the elevation of Lake Tahoe would be comparable to the current regime at an elevation of about 1128 m (e.g., Grass Valley, California).

The impacts of climate change in the Tahoe basin are not merely theoretical, they have already been measured. The observed impacts include the warming of the lake itself, a shift toward earlier snowmelt, a shift from snow to rain, and a change in forest condition. Although any lasting remedy to the problem of global climate change obviously would be global in scope, consideration of the local impacts by resource managers and scientists is appropriate for two reasons. First, the trends in climate may affect efforts to understand the causes of water quality changes in both streams and lakes in the Tahoe basin. Second, it may be possible to mitigate some of the impacts of climate change in the basin.

Knowledge Gaps

Direct hydrologic impacts—

Across the Western United States, the timing of snowmelt has shifted over the last half-century toward dates earlier in the water year (Cayan el al. 2001, Dettinger and Cayan 1995), with the snowmelt flood now running 30 to 40 days earlier in some rivers compared with the pre-1940s record. Using regression analysis of historical data together with a Parallel Climate Model (PCM) to forecast and hindcast air temperature and precipitation, Stewart et al. (2004, 2005) showed that the shift in snowmelt timing will accelerate during this century. This shift in snowmelt timing is largely in response to changes in air temperature rather than precipitation. The PCM, together with a Precipitation-Runoff Model System (PRMS) has also been used to simulate the hydrologic responses to climate change in the nearby Merced, Carson, and American River basins. The results show a recent and likely future shift in the timing of snowmelt runoff, and that the shift began in the early 1970s (Dettinger et al. 2004a, 2004b).

The shift in snowmelt timing is also occurring in the Tahoe basin. An analysis of daily discharge records for Ward, Blackwood, Trout, and Third Creeks and the Upper Truckee River shows an average shift in timing of the annual snowmelt peak discharge of 0.4 day per year since 1962 (fig. 4.8). The shift in timing of the snowmelt peak (after removal of the "total annual snowfall effect") is correlated with the April–June Pacific Decadal Oscillation Index (see Mantua et al. 1997), but it is driven more directly by spring air temperature, which trends upward over the period 1914–2002 (Coats and Winder 2006).

Not only is the timing of snowmelt in the Tahoe basin shifting, but the fraction of precipitation that falls as snow rather than rain is decreasing. From 1914 to 2002, the percentage of total annual precipitation falling as snow at Tahoe City has decreased at an average rate of 0.2 percent per year (fig. 4.9).

Although there is no discernible trend in total annual precipitation at Tahoe City, there is evidence that the frequency of intense rainfall is increasing. Modeling studies have shown that climate warming in the Sierra will increase the magnitude of the 95^{th} percentile daily rainfall amount (3.9 cm/day for the period 1910–2007 at Tahoe City) (Kim 2005). Figure 4.10 shows the trend for number of events

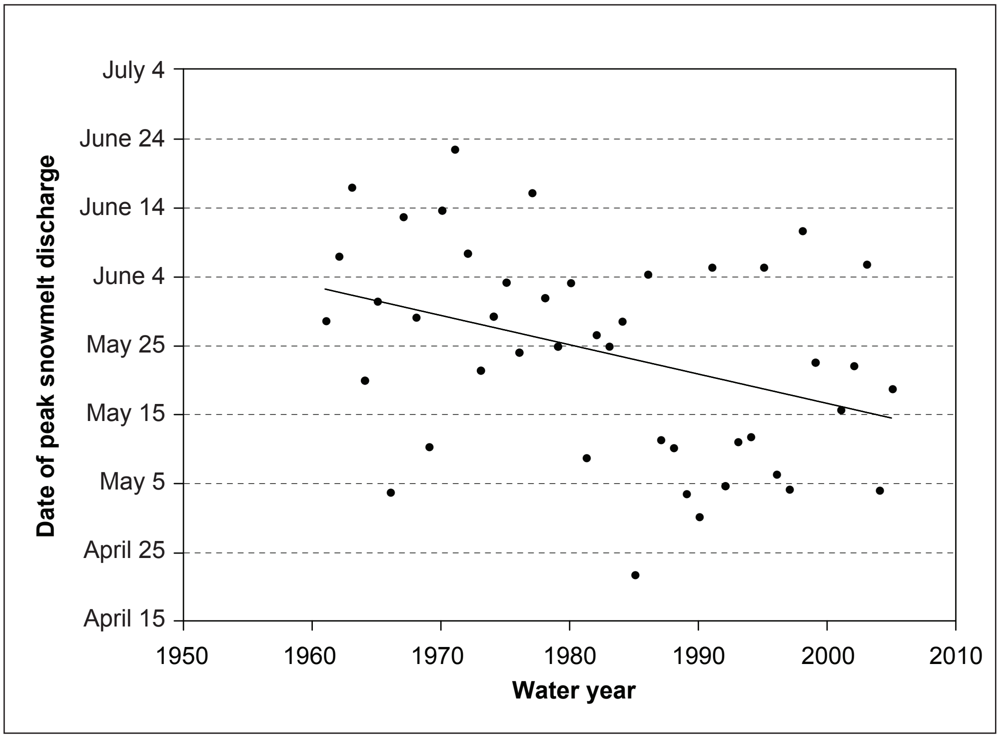

Figure 4.8—Average date of snowmelt peak discharge, for Ward, Blackwood, Third and Trout Creeks, and the Upper Truckee River (from R. Coats). $P = 0.01$, $r^2 = 0.14$.

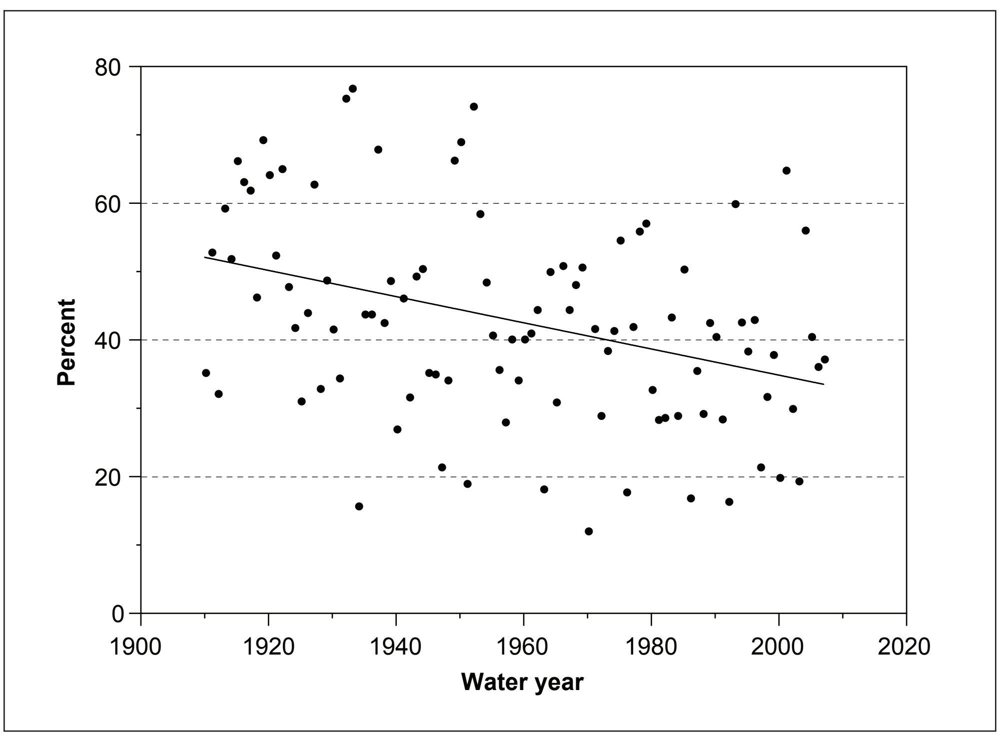

Figure 4.9—The percentage of total annual precipitation falling as snow at Tahoe City, CA (from R. Coats). $P < 0.001$, $r^2 = 0.13$.

exceeding 3.9 cm/day for half-decades since 1910. Most significantly, since 1975, deviations from the upward trend have increased. These changes will likely exacerbate surface soil erosion, especially where appropriate restoration and BMPs have not occurred.

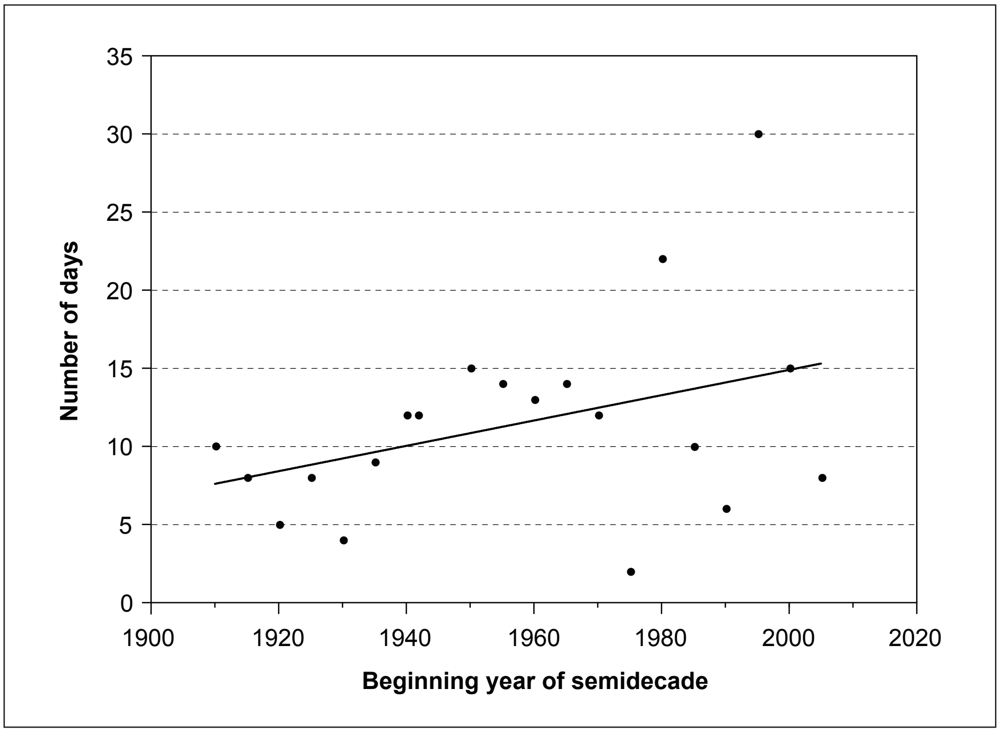

Figure 4.10—Number of days per semidecade with daily rainfall exceeding the 95th percentile daily amount (from R. Coats). $P < 0.1$, $r^2 = 0.14$.

Indirect hydrologic impacts—fire frequency and vegetation—
Large wildfire activity in the West increased dramatically in the mid-1980s, in some regions owing more to climatic change than to land use history (Westerling et al. 2006). In parts of the West, simulations with the PCM have shown that the trend toward increased fire danger will continue at least through this century (Brown et al. 2004), and forest recovery following fire will be strongly influenced by climatic change (McKenzie et al. 2004).

In the Tahoe basin, the threat of severe forest fires is increased not only directly by higher temperatures and lower humidity, but also by the indirect effects of climate and land use history on vegetation and fuel load. Heavy logging in the late 1800s and subsequent fire suppression and exclusion led to the development of dense overstocked stands of Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), white fir (*Abies concolor* Gord. & Glend.) and red fir (*Abies magnifica* A. Murr. Lindl. ex

Hildebr.). During periods of high moisture stress, these stands are vulnerable to bark beetle (*Ips* sp., *Scolytus* sp., and *Dendroctonus* sp.) attack (Manley et al. 2000); the potential growth rate in beetle populations is further enhanced by a warming trend (Logan et al. 2003). This issue is sometimes referred to as the "forest health" problem, but it is also a hydrology and water quality issue, as runoff in the first years following an intense wildfire can carry greatly increased loads of nutrients and fine sediment to the lake (Miller et al. 2006).

Limnological (lake) impacts—

Since 1970, Lake Tahoe has warmed at an average rate of 0.013 °C per year (fig. 4.11). This has increased the thermal stability and resistance to mixing of the lake, reduced the depth of the October thermocline, and shifted the timing of stratification onset toward earlier dates. The warming trend is correlated with both the Pacific Decadal Oscillation and the Monthly El Niño–Southern Oscillation Index, but it results primarily from increasing air temperature, and secondarily from increased downward long-wave radiation (Coats et al. 2006). Some of the resulting impacts to phytoplankton (Winder and Hunter 2008) and invasive warm-water fish (Kamerath et al. 2008, Ngai 2008) have been documented, but many of the water quality impacts from changes in lake thermal structure need more study.

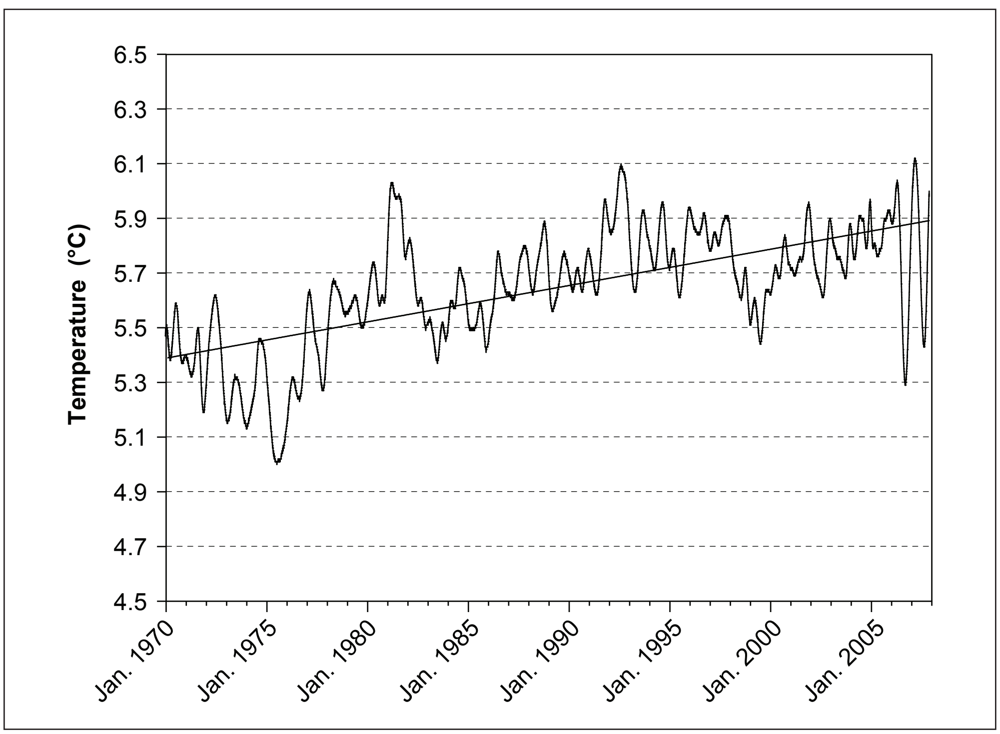

Figure 4.11—The average daily temperature of Lake Tahoe, as deviation from seasonal norm (from R. Coats). P = 0, $r^2 = 0.43$. Average temperature values were calculated as the volume-weighted mean of daily measurements made at 11 depths from the surface to 450 m (near-bottom).

Regional trends in climate change—
Analysis of regional trends in air temperature show that the warming rate at the Tahoe City station (adjusted for the effect of urbanization) is significantly higher (especially in late summer) than at nearby stations outside of the basin. It is also higher than the average for the Sierra region as a whole (see http://www.wrcc.dri.edu/monitor/cal-mon/index.html). This is consistent with the findings for snowmelt timing. Of four streams outside of the Tahoe basin (Sagehen Creek, South Fork Yuba River, and East and West Forks of the Carson River), none showed a shift (1962–2005) in the date of the annual snowmelt peak discharge. The differences in warming rate inside and outside of the basin are striking, and suggest the lake itself may locally enhance the effect of increasing greenhouse gas emission.

Research Needs

- How will the hydrologic changes associated with Tahoe basin warming affect flood frequency, channel change, and sediment/nutrient transport?

The hydrologic changes associated with the present warming trend likely will change the flood-frequency relationships for basin streams, increasing the discharge for a given frequency. The magnitude of the likely changes, however, is unknown. Floods of different recurrence intervals (e.g., the 2-yr flood vs. the 100-yr flood) may be affected differently, and these differences have important implications for channel erosion and sediment transport.

Anderson et al. (2002) showed how down-scaled historical climatic data can be used to analyze flood frequencies using Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). For predicting future trends, the PCM output can be down-scaled and coupled to a hydrologic model, but at the extremes (infrequent high and low flow) it does not reproduce actual streamflow very well (Dettinger et al. 2004b). If a solution to that problem cannot be found, another General Circulation Model might be coupled with one of several watershed models (e.g., HEC-HMS, Hydrologic Simulation Program FORTRAN, PRMS) to model the effects of climate change on flood frequency in selected watersheds in the Tahoe basin.

It is also recommended that existing management models applied in the Tahoe basin as well as new models be used to estimate changes in nutrient and sediment loading to Lake Tahoe. Ideally, such models would consider various surrounding land use types based on anticipated levels of precipitation and runoff predicted by climate change. The event mean concentrations for these pollutants are currently based on existing precipitation conditions. Updated estimates of event mean concentrations based on projected conditions of changes in total precipitation, rain/snow regime, or timing are recommended.

- How will the shift in snowmelt timing and sediment delivery interact with increasing lake temperature and thermal stability to affect lake biology and water clarity? How will the insertion depth of stream inflow be affected?

The LCM, used to model changes in lake water quality, will be used, together with down-scaled PCM meteorology, to address these questions. Future climate change scenarios will be used to generate input data sets to predict future trends in lake temperature, thermal structure, and mixing conditions. These results will then be combined with the output from the LSPC watershed model of the Tahoe basin (Riverson et al. 2005)—run under meteorological conditions defined by PCM output—to evaluate changes in water clarity and primary productivity that may result from simultaneous changes in lake thermal structure, watershed hydrology and sediment/nutrient loading. A sensitivity analysis of the combined model could help determine the extent to which lake clarity can be improved in an era of climate warming by efforts to reduce the input of fine sediment and nutrients.

Little is known about the likely direct and indirect effects of lake warming on lake ecology. Recent studies have shown some effects of lake warming on phytoplankton and fish. This work needs to be continued and extended to include the effects of lake warming on the microbial food web and zooplankton.

- How will the increase in lake temperature and thermal stability affect Lake Tahoe's dissolved oxygen (DO) profile? Is it possible for the lake to go anaerobic at the bottom?

The trends in lake temperature and thermal stability, combined with increasing primary productivity, will increase the fall/winter biochemical oxygen demand in the water column, while decreasing the solubility of oxygen, and possibly the downward transport of DO. The DO during spring and summer phytoplankton blooms may increase at some depths. Coupling the LCM to a climate model such as the PCM could help to assess how lake warming will affect the DO profile. The analysis could be combined with a study to sort out the impacts of combined lake warming and watershed change. The modeling could be combined with measurements of water column DO (ongoing), as well as careful measurement of redox potential across the sediment-water interface at the bottom of the lake.

- Does Lake Tahoe enhance the rate of climate change in the basin?

The trends in both air temperature and snowmelt timing indicate that the Tahoe basin is warming faster than the surrounding region. With a low albedo and high heat storage capacity relative to the land surface, much of the short-wave energy striking the lake surface is stored and released later as latent and sensible heat, and long-wave radiation. The outgoing long-wave energy from the lake (and overlying atmospheric boundary layer) is thus higher than it would be absent the lake. As greenhouse gas concentrations increase, the rate of increase in energy absorption above the lake should exceed that above the land. A coupled lake-atmosphere climate model embedded in a General Circulation Model is needed to test this “lake climate change enhancement hypothesis.” If the results strongly support the hypothesis, they would indicate that the Tahoe basin is especially sensitive to the impacts of greenhouse gas emissions, and that planning is urgently needed to address the impacts of climate change in the basin.

- What impact will potential changes to watershed hydrology and pollutant loading have on current management strategies to restore Lake Tahoe’s water clarity?

Based on current and new research, resource managers will want to know how to address the potential for increased pollutant loading to Lake Tahoe as the result of changes in precipitation patterns. Such information is best obtained at the BMP project scale, the individual watershed scale, and the entire drainage basin scale.

Water Quality Research Priorities

Many of the current key management questions for water quality focus on the “pollutant pathway.” Topics include source identification, transport within the watershed, control and abatement, defining loads to the tributaries and the lake, fate of fine sediments and nutrients in the lake, and assessment of water quality response.

Research and monitoring efforts supported by the LTIMP, the Lake Tahoe TMDL Research Program, the Southern Nevada Public Lands Management Act, the Environmental Improvement Program, and many individual science projects funded by federal, state, and local governments, have resulted in a greater level of understanding of water quality in the Tahoe basin than at any previous time. Much of this information has been directly used in the development of new and innovative water quality management strategies (e.g., the Lake Tahoe TMDL).

As water quality improvement projects have been implemented and research and monitoring data have been collected, a number of future research needs have emerged in the area of water quality. Topics of research priority in this context are those that are needed by managers within the next 3 to 5 years to support current and developing water quality strategies.

For the water quality research priorities presented here, the authors have intentionally developed a series of topic areas rather than presenting detailed testable hypotheses because (1) researchers are making rapid progress in many of the water quality subthemes discussed above, (2) hypotheses and details change quickly, and (3) researchers and water quality agencies at Lake Tahoe have developed a flexible and dynamic approach toward setting priorities for specific investigations based on scientific merit and relevancy.

Based on all these considerations, and guided in part by the identification of the key drivers and linkages in the conceptual model (fig. 4.1), the water quality research priorities are as follows:

Pollutant loading and treatment (PLT) within the urban landscape—
PLT1. Develop a process-based understanding of sources, transport, and loading of fine sediment particles (<16 µm) from different urbanized land uses in the Tahoe basin. While this includes all features of the urban landscape, roadways appear to be particularly important and deserve focused attention.

PLT2. Quantify the effectiveness of BMPs and other watershed restoration activities on the control of fine sediment particle and nutrient loading to Lake Tahoe. Major load reduction approaches include hydrologic source control (HSC), pollutant source control (PSC) and storm water treatment (SWT). Although some data have been collected on BMP and restoration effectiveness in removing nutrients and fine sediment, these efforts have been for specific projects and have not provided basinwide process-based evaluations. A comprehensive basinwide watershed-scale evaluation of BMP and erosion control project effectiveness is needed, especially for the Lake Tahoe TMDL program.

PLT3. Conduct focused studies to understand the influence that altered urban hydrology has on pollutant pathways and determine how alternative hydrologic designs can enhance load reduction.

PLT4. Investigate longer term impacts from infiltration of stormwater runoff around the Tahoe basin, particularly as it relates to different soils, land uses, and ground-water quality.

PLT5. Continue efforts to establish a Regional Storm Water Monitoring Program. Key elements of this program include (1) pollutant source monitoring; (2) pollutant reduction monitoring; (3) BMP design, operation, and maintenance monitoring; and (4) data management, analysis, and dissemination. Although this is not research per se, data collected under this program will be used to support research on BMPs and pollutant load reduction as described in this chapter.

PLT6. Validate pollutant reduction crediting tools that are currently being developed to track progress in implementing the Lake Tahoe TMDL. At the same time, develop a science-based adaptive management program to guide pollutant load reduction activities.

Near-shore (NS) water quality and aquatic ecology—

NS1. Research is needed to determine near-shore processes at various temporal and spatial scales. This research will contribute to an integrated data base that can be used to determine trends and patterns for integrated, process-driven models. From this information, construct a predictive model to help guide ongoing and future management strategies. It is recommended that this model include features such as nutrient loading, turbidity, localized and lakewide circulation patterns, wave re-suspension, periphyton and macrophyte populations, introduced and native species, recreational uses, and activities within the near shore.

NS2. Develop an aquatic invasive species research program with direct ties to water quality (e.g., risk of invasive species on native species composition and aquatic food webs, in-lake sources of drinking water, or water quality and stimulation of benthic algal growth in the near shore).

NS3. Develop analytical approaches for establishing quantitative and realistic water quality standards and environmental thresholds for the near-shore region.

Erosion and pollutant transport (EPT)/reduction within the vegetated landscape—

EPT1. Collaboration between researchers and agency representatives is recommended to evaluate fine sediment and nutrient loads resulting from forest fuels reduction activities. A major effort would include quantifying BMP effectiveness for controlling fine sediment and nutrient releases from wildfire, as well as from forest biomass management practices, such as prescribed fire and mechanical treatment.

EPT2. Fully evaluate the benefits and risks from using large areas of the natural landscape (e.g., forests, meadows, flood plains, wetlands) for treatment of urban runoff.

Water quality modeling (WQM)—

WQM1. Water quality management in the Tahoe basin has embarked on a pathway that will use science-based models to help guide management into the future. It is recommended that support continue for the development, calibration, and validation of these models.

WQM2. Develop appropriate linkages among the landscape, climate, and atmospheric and water quality models to provide more comprehensive assessment of primary and secondary drivers whose effects propagate through the ecosystem.

WQM3. Build decision-support modules for the linked ecosystem models that will support evaluation of effects from larger spatial scales.

Climate change (CC)—

CC1. Continue to document the effects of climate change on existing and future water quality conditions.

CC2. Apply predictive scenario testing for evaluating potential effects from climate change within the new and developing management models used for water quality in the Tahoe basin. In particular, it is recommended that models be used to evaluate basinwide BMP effectiveness and load reduction strategies based on the expected changes to temperature, precipitation, and hydrology.

CC3. Limnological processes in Lake Tahoe such as stratification, depth of mixing, particle distribution and aggregation, species succession, aquatic habitat based on water temperature, and meteorology could all benefit from reevaluation in light of climate change and possible management response to the impacts of climate change.

English Equivalents:

When you know:	Multiply by:	To get:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles
Hectares (ha)	2.47	Acres
Square meters (m^2)	10.76	Square feet
Square kilometers (km^2)	.386	Square miles
Grams (g)	.0352	Ounces
Kilograms (km)	2.205	Pounds
Tonnes or megagrams (Mg)	1.102	Tons
Kilograms per hectare (kg/ha)	.893	Pounds per acre
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit

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