- 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

[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 95th 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

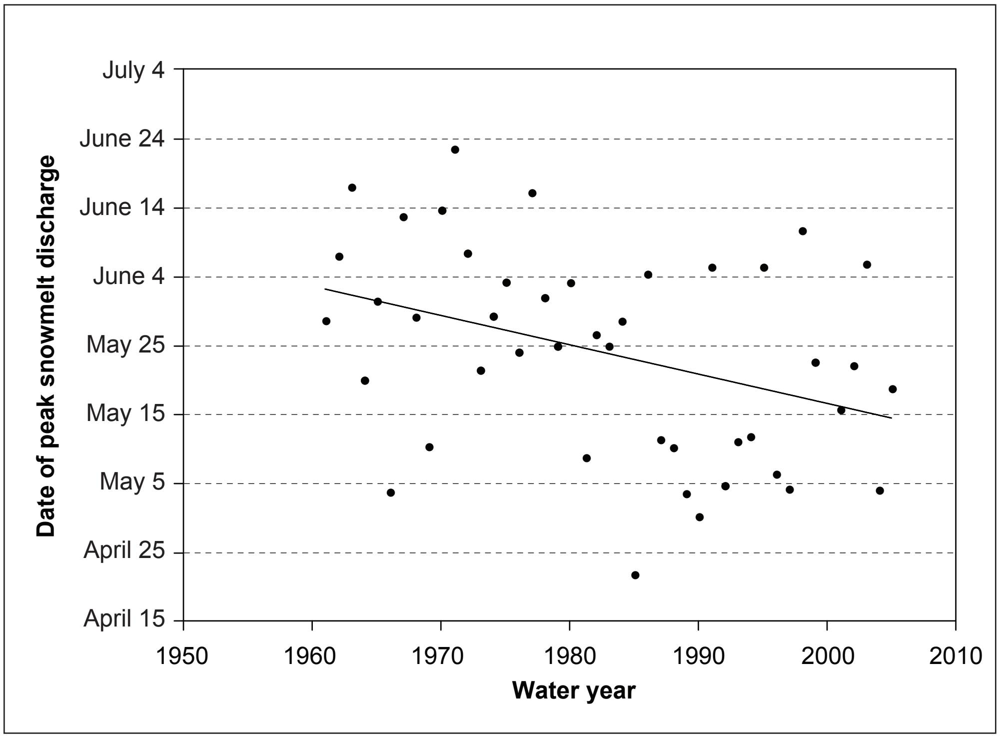

Figure 4.8—Average date of snowmelt peak discharge, for Ward, Blackwood, Third and Trout Creeks, and the Upper Truckee River (from R. Coats). $P = 0.01$, $r^2 = 0.14$.

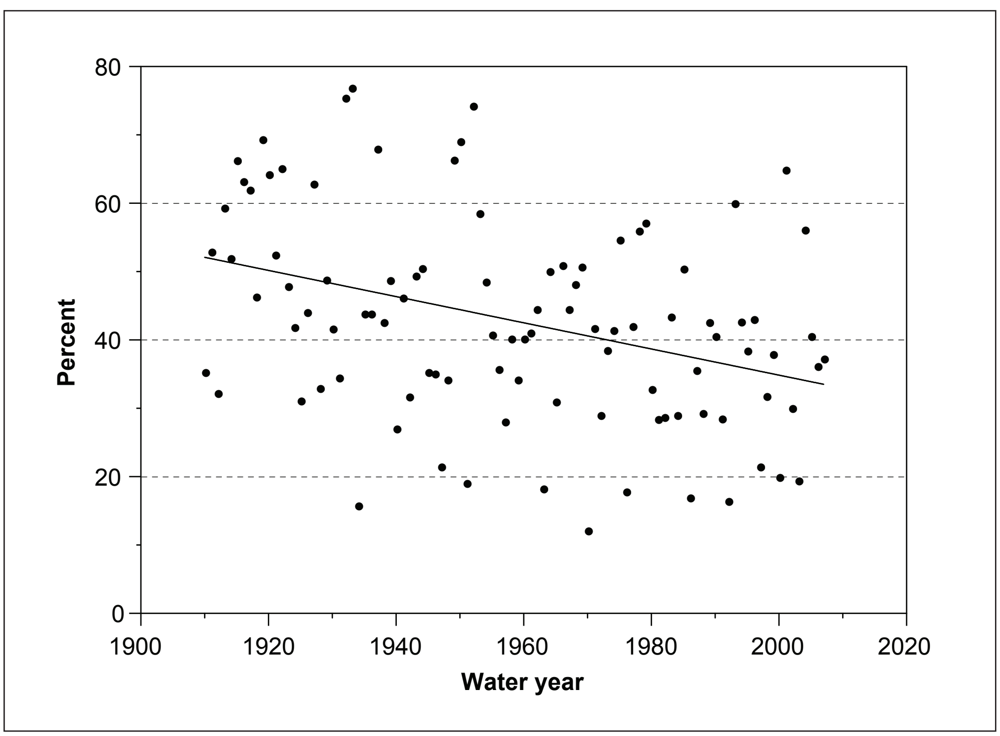

Figure 4.9—The percentage of total annual precipitation falling as snow at Tahoe City, CA (from R. Coats). $P < 0.001$, $r^2 = 0.13$.

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.

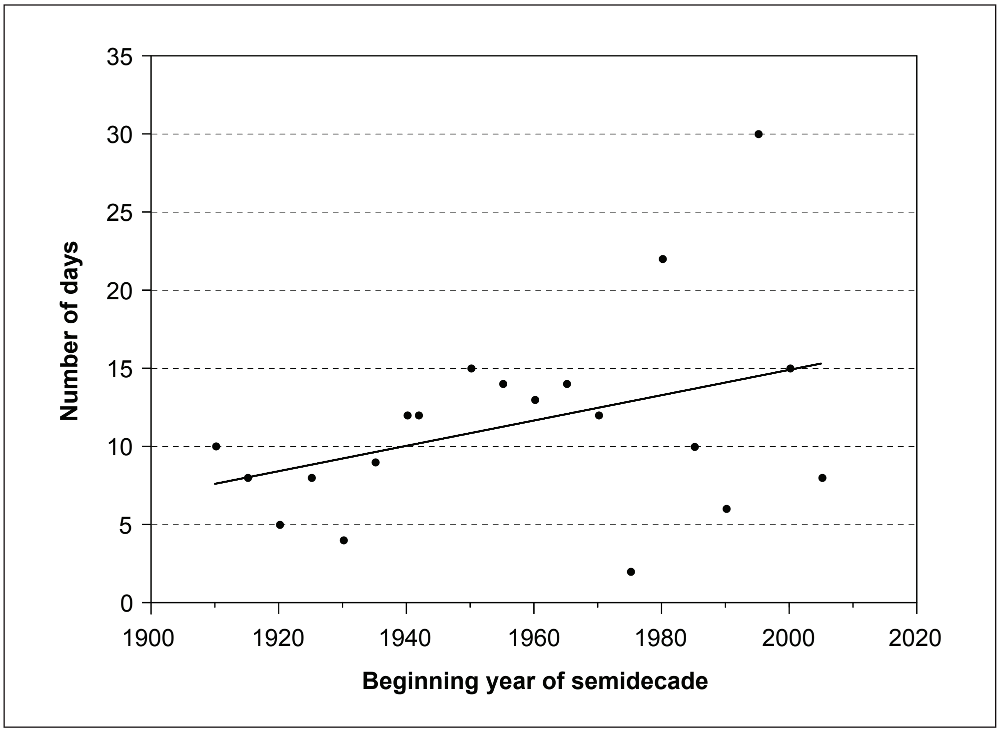

Figure 4.10—Number of days per semidecade with daily rainfall exceeding the 95th percentile daily amount (from R. Coats). $P < 0.1$, $r^2 = 0.14$.

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.

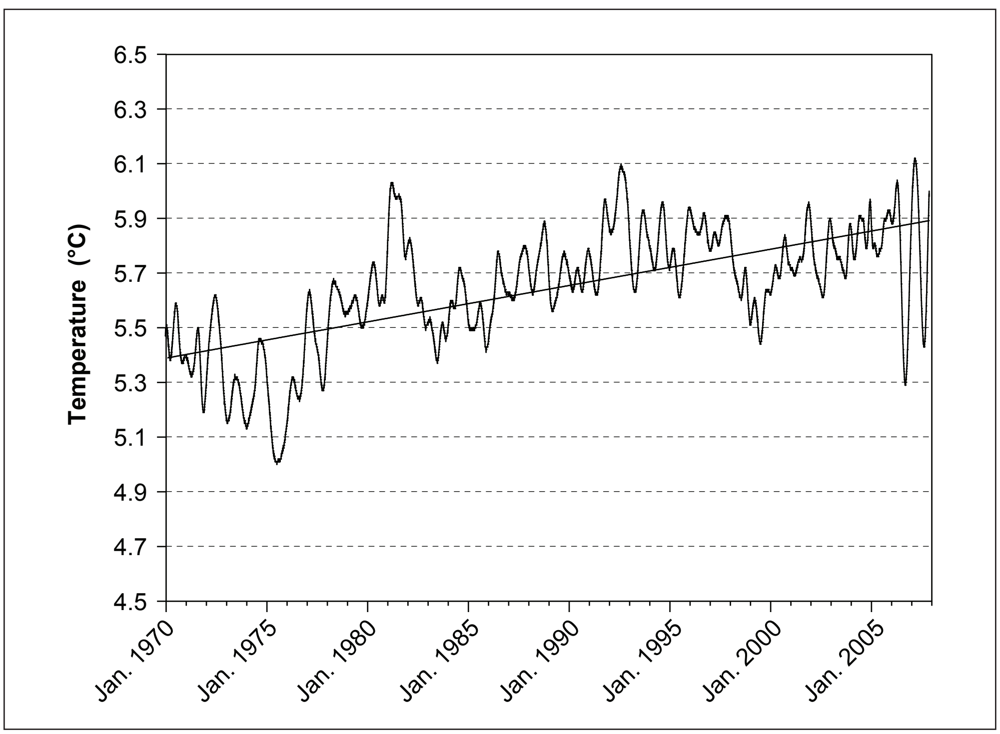

Figure 4.11—The average daily temperature of Lake Tahoe, as deviation from seasonal norm (from R. Coats). P = 0, $r^2 = 0.43$. Average temperature values were calculated as the volume-weighted mean of daily measurements made at 11 depths from the surface to 450 m (near-bottom).

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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