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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.

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

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Abstract

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An integrated science plan was developed to identify and refine contemporary science information needs for the Lake Tahoe basin ecosystem. The main objectives were to describe a conceptual framework for an integrated science program, and to develop research strategies addressing key uncertainties and information gaps that challenge government agencies in the theme areas of (1) air quality, (2) water quality, (3) soil conservation, (4) ecology and biodiversity, and (5) integrating the social sciences in research planning. Each strategy concludes with a presentation of near-term research priorities. Several factors (e.g., changing agency priorities, funding levels, and the emergence of new issues, new information, or new technologies) can affect the applicability of near-term research priorities. Thus, this science plan is considered a living document. The research priorities are best reviewed and revised regularly to ensure they reflect the changing information needs and evolving priorities of agencies charged with the welfare of the Lake Tahoe basin.

Keywords: Lake Tahoe basin, air quality, water quality, soil conservation, ecology and biodiversity, social sciences.

Summary

The known effects of past actions and the unique character of the Lake Tahoe basin have led to broad-based support for substantive conservation and restoration efforts over the last two decades. Increased attention and funding over the past decade, in particular, have resulted in remarkable progress toward restoration goals, along with considerable information on the strengths and weaknesses of different approaches to addressing the substantial restoration challenges. Restoration has focused not only on Lake Tahoe, but also on the entire watershed. Special attention has been given to the highly interdependent nature of terrestrial and aquatic habitats and the multifaceted socioeconomic conditions that influence the Tahoe basin ecosystem. The Lake Tahoe basin is recognized as a highly complex physical, biological, and social environment, and the challenges posed by its restoration and continued management for multiple benefits are paralleled by few other locations.

Conservation and restoration of the Lake Tahoe basin ecosystem have required the sustained engagement of federal, state, and local governments, as well as the private sector. These entities have worked together to develop and implement a variety of programs and activities aimed at achieving common environmental and social goals. Yet determining how to proceed with conservation and restoration efforts in the face of limited information remains a central challenge to these efforts. Science (e.g., monitoring, research, and modeling), particularly applied science to inform adaptive management, provides a promising set of tools to address information limitations that affect our ability to select and implement effective management strategies. However, effort is required to organize and describe the science activities needed to inform adaptive management focusing on the conservation and restoration of a complex system. This document presents the results of science community efforts to organize and describe the initial elements of an integrated science plan for the Lake Tahoe basin: a conceptual framework for completing science to inform adaptive management, and focused research strategies covering topic areas of relevance to Tahoe basin management and conservation. Separate, agency-led efforts are underway to develop other essential elements of an integrated science plan including programs for status and trends and effectiveness monitoring, new data applications aimed at converting data into information and knowledge, and the integration of monitoring and applied research efforts.

This science plan was developed to identify and refine science information needs for the Lake Tahoe basin. The main purpose of this effort was to develop a set of research strategies addressing key uncertainties and information gaps that challenge resource management and regulatory agencies. The research needs

identified in these strategies are based on assessments of the issues and information needs that currently confront government agencies and stakeholders working in the basin. The resulting strategies are intended to guide future research efforts and to help maximize the information gained from future science investments. Three common needs drive the recommendations presented in each research strategy:

- Increasing our understanding of the factors and processes driving change.
- Developing the tools and knowledge to predict future conditions in the Lake Tahoe basin and permit comparisons among alternative futures.
- Providing information for future management decisions aimed at conserving and restoring the natural and human environments of the Lake Tahoe basin.

This science plan comprises seven chapters. Chapter 1 examines the need and approach for developing the science plan, and also provides important contextual information. A brief review of past science planning efforts presented in chapter 1 shows that merely producing a science plan is not enough to ensure the establishment of a sustained science program that can deliver useful information covering a diversity of issues. Clear policy direction to obtain and use scientific information is essential, but a deeper level of commitment among all relevant parties will guide progress from planning to implementation. An explicit assumption of this effort is that the agencies charged with responsibility for the welfare of the Lake Tahoe basin will collaborate to establish the funding, resources, and infrastructure necessary for sustained implementation of an applied science program. Brief summaries and recommended priority science needs for each of the six remaining chapters are presented below.

Conceptual Framework for an Integrated Science Plan

Conceptually, the efforts and activities of an integrated science program can be divided among three basic elements: (1) monitoring, (2) empirical research, and (3) data application. To be effective, however, it is recommended that efforts be integrated across all three elements and applied to land and resource management efforts through adaptive management. This is the basis for the conceptual framework presented in chapter 2. The overview conceptual model presented in this chapter will orient readers to the important issues covered in this science plan, the relationships among those issues, and the format of more specific conceptual models presented in each of the research strategies. Near-term priorities for each science activity are as follows:

Monitoring—

Effective monitoring schemes are essential elements in integrated science programs. Monitoring results are often the main source of scientific information in support of adaptive management systems. Monitoring is used to establish baseline conditions, track management activities, and record outcomes. Several monitoring needs were identified in discussions between scientists and managers during the course of developing this science plan. What emerged from those discussions is not a comprehensive list of the monitoring needs for the Lake Tahoe basin; rather, the list represents the recommended highest priority monitoring information needs to be addressed within the next five years.

- Meteorology and climate change:
    - Long-term acquisition of spatially relevant meteorological data on air temperature; wind-speed and direction; humidity; precipitation timing, amount, and type; streamflow; snowpack; and snowmelt are recommended to support environmental studies in all issue areas. The technology to capture these kinds of data has advanced, which allows them to be collected more efficiently at more locations than in the past. These data are fundamental to informing questions about air quality, water quality, soil conservation, ecology and biodiversity, and climate change.
- Air quality:
    - Improve air quality monitoring in the Tahoe basin. The first step is to develop a comprehensive monitoring plan for the basin that addresses the criteria air pollutants (covered under the National Ambient Air Quality Standards) and species affecting human and ecosystem health (including water clarity), along with the required spatial and temporal distribution of the measurements. Once this plan is prepared, sampling locations can be chosen and appropriate air quality sensors can be deployed. Air quality and meteorological monitoring are best integrated to maximize efficiencies and information gain.
- Water quality:
    - Initiate long-term status and trend monitoring of watershed hydrology and pollutant loads entering Lake Tahoe to (1) inform Lake Tahoe total maximum daily load (TMDL) land use and lake clarity models, and other water quality-related management models; (2) evaluate progress in meeting TMDL allocation requirements and other regulatory obligations; and (3) evaluate snowpack and snowmelt trends as they pertain to lake clarity. The Lake Tahoe Interagency Monitoring Program (LTIMP)

partially meets these monitoring needs, but this program has eroded over the last decade owing to funding restrictions. The LTIMP does not include some key pollutant sources (i.e., urban stormwater and road runoff), and it does not include some key water quality constituents that directly affect lake clarity (i.e., particle number and particle size distribution).

  - Develop a regional stormwater quality/best management practices retrofit monitoring program to assess the effects and effectiveness of capital investment projects at the project, watershed, and basinwide scales.

- Soil conservation:
  - Implement a consistent and effective monitoring protocol for key soil properties and conditions that is process-specific, uniform across agencies and contractors, and relies on current technology. Such a monitoring program is considered vital to informing the performance effectiveness of projects affecting soil properties and conditions throughout the Tahoe basin.

- Ecology and biodiversity:
  - Develop a forest fuel reduction monitoring program to assess quantitatively the effects and effectiveness of fuel reduction projects at the project, watershed, and basinwide scales.
  - Establish a long-term, basinwide status and trend monitoring program for terrestrial and aquatic biotic communities. It is recommended that biodiversity monitoring focus on the composition of biotic communities and the distribution, frequency of occurrence, and abundance of associated native and nonnative species using direct measures and indicators to inform environmental thresholds and desired conditions. Monitoring data also could provide a foundation for assessing the effects of climate change on terrestrial and aquatic biota of the Lake Tahoe basin.
  - Initiate status and trends monitoring for select focal species identified in regulations and basin management plans. Integration of focal species monitoring with biodiversity monitoring is recommended to the degree efficiencies can be gained, and to provide reliable estimates of the population parameters targeted in those regulations and plans.

- Social sciences:
  - Establish regular and systematic surveys to document the use of existing recreation resources and to help inform priorities for future facilities.

- Develop and implement infrastructure and common methods to collect basic social and economic data throughout the Lake Tahoe basin. Common sampling methods are recommended to ensure that data can be aggregated and analyzed to assess socioeconomic conditions within the various municipalities, within geographic regions, and throughout the entire basin.
- Develop infrastructure to support the centralized collection, inventory, and distribution of transportation data at regional and basinwide levels.
- Establish a spatially and temporally appropriate monitoring program to allow for the assessment of noise conditions relative to established threshold indicators.

Empirical research—

Research can be defined as a structured process of inquiry that aspires to discover, interpret, and revise our knowledge of facts. Research aims to produce an ever-greater knowledge of events, behaviors, processes, theories, and laws. Research may include laboratory or field experiments, or the development of models. Research is one of the fundamental ways in which science contributes to reducing uncertainties. Research and monitoring operate most effectively together. The single highest priority for research is to establish a stable funding stream to ensure that the level of scientific understanding of the Lake Tahoe basin continues to develop in order to support timely and effective science delivery and inform policy choices and management strategies. Specific, near-term research priorities are presented below for each research strategy included in this science plan.

Data application—

Data application includes analysis, reporting, management, and assessment to accomplish the following objectives (1) manage data and information in ways that ensure their quality and availability; (2) complete analyses that convert data into information that can directly guide management; and (3) share that information with others, such that information promotes knowledge. From a management standpoint, data application to real-world problems may be the most important element of an integrated science program, because it is this activity that provides research and monitoring results in forms that managers can apply directly to management actions, decisions, and policy choices. A dedicated source of funds and resources to support data management, analysis, and reporting together with the identification of responsible entities are recommended to ensure that this element of an integrated science program is accomplished and maintained, and that redundant efforts are eliminated. In the course of developing this science plan, a number of high-priority investments in data applications were identified for completion over the next 5 years.

- **Accomplishments report**: Completed annually, an accomplishments report from the science community would synthesize the results of research and other science projects completed during the previous year; this report can then be combined with updated running totals of administrative outcomes (e.g., dollars spent, number of projects completed) and program outcomes (e.g., acres restored, volume of storm water treated) from the management agencies. The accomplishments report would summarize scientific findings and relate the importance of those findings to ongoing and future management activities and policies. This report also could identify research needs that have emerged as a result of monitoring results, new environmental conditions, or changes in policy or regulation. Information in the accomplishments report will help agencies and scientists track projects completed or in progress, and develop or adjust near-term priorities for capital projects, research, monitoring, and analysis. Information in the report also could provide a snapshot of project outcomes.
- **Central monitoring database**: The value provided by a centralized information depository is manifold; however, a primary goal is to promote the management of both research and monitoring data in a manner that ensures their quality and accessibility. It is recommended that infrastructure be developed and maintained so that basic data and summary information are stored, integrated, and accessible to a diversity of users. The Tahoe Integrated Information Management System (TIIMS) has begun efforts to address the needs associated with this activity, but more work remains.
- **Environmental management knowledge base**: Create an environmental management knowledge base that documents our current understanding of conditions, interactions, threats, and desired outcomes. Use the outputs of this knowledge base to inform science and management priorities and activities. Integrated information systems can meet the array of information needs across institutions and disciplines in an efficient and transparent manner. Knowledge bases with their incumbent conceptual models provide valuable tools for integrated information storage and retrieval. A knowledge base system of environmental quality for Lake Tahoe that serves both management and research would:
    - Provide a transparent basis for evaluating desired conditions
    - Enhance the ability to communicate ideas and outcomes among stakeholders regarding management options at site and landscape scales
    - Facilitate rapid access by decisionmakers to needed information

    - Help prioritize information gaps to be filled, and illustrate the basis of priorities
    - Compare outcomes associated with various management options to help determine priority objectives for specific locations and how to balance objectives across landscapes
    - Serve as a tool to interpret changes in desired conditions over time, based on monitoring data.

- **State of the Lake Tahoe basin report**: Completed every fifth year, a state-of-the-basin report would include a comprehensive synthesis of the research and monitoring that has been completed over the previous 5 years. Results could be framed in terms of an environmental report card for the Lake Tahoe basin, which would evaluate conditions relative to environmental goals and thresholds. This information would be available for use in evaluating and (if necessary) modifying management strategies and implementation programs (i.e., informing the adaptive management process). This report also could alert high-level officials to emerging issues that may require new or alternative policies. The state of the Lake Tahoe Basin report would include the following subject areas:
    - Lake Tahoe
    - Basin watershed condition
    - Basin airshed condition
    - Living resources condition
    - Human environment.

Air Quality

Chapter 3 addresses the fact that air quality in the Lake Tahoe basin is known to affect lake water quality, forest health, and human health. To address these issues and develop a sound scientific approach for mitigating the impacts of atmospheric pollutants, this research strategy provides an update and builds on recent work to understand how changes in air quality affect various aspects of the natural and human environment in the Lake Tahoe basin. This chapter also delineates current knowledge gaps and defines the research needs and strategies to close those gaps. Near-term air quality research priorities are as follows:

- Many of the key chemical species and physical parameters leading to secondary pollutant formation and/or deposition to the lake are not currently measured. Air quality measurements of key species under a range of meteorological conditions and averaging times are recommended following the development of a monitoring plan (see air quality monitoring description above). Parameters to measure include nitrous oxides, ammonia, nitric acid; size-segregated aerosol mass; particle number and size distribution, and aerosol chemical composition. Once these data are obtained, it will be possible to assess atmospheric impacts and air pollutant trends. This information also will provide the necessary input for developing an understanding of the processes controlling air quality and atmospheric deposition in the basin.

- The only model adapted for use in the Tahoe basin is the Lake Tahoe Atmospheric Model, a heuristic model that is based on statistical input. It is recommended that an appropriate air quality model incorporating physical processes be developed that can utilize the full suite of meteorological, chemical, and particulate data. This will enable managers and scientists to better assess air pollutant trends, estimate impacts, and support the development of effective regulations that will assist in meeting air quality and other environmental goals.
- Atmospheric deposition to the lake is the major source of nitrogen and a substantial source of phosphorous and particulate matter. There is, however, significant uncertainty in deposition flux estimates. To reduce this uncertainty, it is recommended that focused studies (i.e., gradient or eddy-correlation studies, along with measurements of key species) be conducted of the sources and pathways of particle deposition to better inform models and restoration efforts.
- Mobile source emissions are a major source of pollutants in the basin. To improve the emissions inventory, it is recommended that Tahoe-specific vehicle model year distributions, emission factors, and activity data be conducted for use in mobile source emission factor models. These results will reduce the uncertainty in the emissions inventory and enable regulators to develop more effective strategies to reduce pollution in the basin.

Water Quality

Lake Tahoe is the most-studied feature of the Tahoe basin ecosystem with regard to water quality. Although a substantial amount of research and monitoring has been accomplished, knowledge gaps and uncertainties still exist, particularly in understanding how watershed restoration efforts influence the long-term water quality of Lake Tahoe. Because water quality restoration efforts in the Tahoe basin are expected to exceed $1 billion, it is critical that we continue to collect and deliver information in an organized fashion. The water quality research strategy in chapter

4 is intended to serve as a road map for discussions with resource managers. The chapter identifies those science projects necessary to help guide water quality restoration efforts and understand related ecosystem processes. Near-term water quality research priorities include:

- Pollutant loading and treatment within the urban landscape:
  - Develop a process-based understanding of sources, transport and loading of fine sediment particles (<20 µm) from different urbanized land uses in the Tahoe basin. Although this includes all features of the urban landscape, roadways appear to be particularly important and deserve focused attention.
  - Quantify the effectiveness of best management practices (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 stormwater 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.
  - Conduct focused studies to understand the influence altered urban hydrology has on pollutant pathways and determine how alternative hydrologic designs can enhance load reduction.
  - Investigate longer-term impacts from infiltration of stormwater runoff around the Tahoe basin, particularly as it relates to different soils, land uses, and groundwater quality.
  - 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.
  - 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 water quality and aquatic ecology:
  - Additional research is recommended to determine near-shore processes at various temporal and spatial scales. This research will contribute to an integrated database 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. Ideally, this model would include features such as nutrient loading, turbidity, localized and lakewide circulation patterns, wave resuspension, periphyton and macrophyte populations, introduced and native species, and recreational uses and activities within the near shore.
  - Develop an aquatic invasive species research program with direct ties to water quality (e.g., threat of invasive species impacts on: [1] native species composition and aquatic food webs, [2] in-lake sources of drinking water, or [3] water quality and stimulation of benthic algal growth in the near shore).
  - Develop analytical approaches for establishing quantitative and realistic water quality standards and environmental thresholds for the near-shore region.

- Erosion and pollutant transport/reduction within the vegetated landscape:
  - 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.
  - 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:
  - 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. Continued support for the development, calibration, and validation of these models is recommended.
  - Develop appropriate linkages between 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.

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

- Climate change:
  - Continue to document the effects of climate change on existing and future water quality conditions.
  - 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, models could be used to evaluate basinwide BMP effectiveness and load reduction strategies based on the expected changes to temperature, precipitation, and hydrology.
  - 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 are all recommended for reevaluation in light of climate change and possible management response to the impacts of climate change.

Soil Conservation

Today soil conservation conveys a concept much broader than preventing soil erosion and reclaiming eroded lands. Soil conservation strategies go well beyond simply protecting soil from processes of physical erosion to now encompassing the protection and enhancement of overall soil quality and ecology. The intent of chapter 5 is to identify the most pressing management questions, uncertainties, and pertinent research needed to address a wide spectrum of plant-, soil-, and water-related issues in the Lake Tahoe basin. Near-term soil conservation research priorities include:

- Key soil properties and conditions:
  - Further quantify the distribution of various watershed properties such as soil water repellency, biologic and inorganic nutrient pools, infiltrability, and water balance parameters on a larger spatial scale. The impact of natural and anthropogenic activities such as development (impervious vs. pervious), forest management (fire suppression vs. mechanical or prescribed fire biomass reduction), vegetation (native vs. nonnative species), restoration (physical and chemical amendments vs. reduced fertilization), and features that have disrupted natural littoral and eolian processes on soil health at the watershed scale (including the intervening zones) remains poorly understood.

- Quantitatively assess which restoration methods are most effective in controlling event-based runoff and the transport and equilibrium chemistry of fine particles most associated with nutrient and sediment loading. Project success and longevity would be evaluated relative to the sustainability of hydrologic function, productivity, and erosion control over time.
- Characterize to the extent feasible and quantify where possible historical vs. current and natural vs. anthropogenic induced declines in soil status and resulting soil loss at the watershed scale. Research on soils in natural as well as disturbed settings is recommended whenever possible, with sites established to measure soil conservation parameters including inputs such as plant-soil nutrient fluxes through litter-fall, crown-wash, and root turnover as well as losses from erosion, leaching, runoff, wind, or fire. Research would focus on sites where a suitable control portion is available, especially if event (e.g., prewildfire or pretreatment) data are available.

***Knowledge advancement potential*—**The fate of Sierran ecosystems in a changing environment will have a direct impact on soil health, fire hazard, biomass mitigation strategies, erosion, and water quality. Manipulative research projects that include random assignment of treatments and replication are challenging to perform in the Tahoe basin. And yet a crucial research need is to identify and quantify key indicator parameters in a variety of historical and current ecological settings, under various manipulations, and over time. In such cases where robust experiments are possible, restoration methods that are most effective in controlling runoff and transport of fine particles, as well as those most effective in the reduction of nutrient discharge loading and its direct effect on water clarity can be better assessed. This would allow a more complete understanding of the environmental factors (i.e., temperature, moisture, vegetation, and litter) that determine the formation, persistence, and dissipation of seasonal and long-term effects on runoff water quality and erosion. In this context, similar slope stabilization, infiltration, revegetation, or sedimentation techniques could be tested against each other in similar and divergent environments as a means of ascertaining why some work better than others in one locale vs. another. Research focused on the identification, monitoring, evaluation, tracking and adaptive management of individual and collective BMP systems, and linking them to geographic information system layers at the watershed and basin scale would go a long way toward addressing the concerns of stakeholders and agencies alike. Being able to track and revisit BMP strategies would further facilitate true adaptive management.

- Development and application of predictive models as related to soil conservation:
  - Successful model application dictates the need for site-specific parameterization and model calibration. Model use and application can then become more consistent, and interpretive assessment more uniform among agencies basinwide. Research and monitoring protocols are recommended to provide relevant information for predictive model development, improvement, calibration, and field validation specific to the Lake Tahoe basin. Prioritization is recommended to determine which soil, vegetation, and hydrologic parameters are important; what should be measured; and what information is needed to parameterize and calibrate the models.
  - Develop a spatially explicit water balance, nutrient cycling, and erosion potential model to better understand current sediment and nutrient transport at the watershed scale and under conditions of potential changes in hydrologic and soil parameters. Further studies of the role of hydrophobic soils are recommended to determine the spatial distribution of recharge areas vs. those that are overland flow generating, and their influence on soil erosion model output estimates. A prioritization of which parameters are important, what should be measured, and what information is needed to parameterize and calibrate the models is recommended.
  - Develop a better understanding of how various factors or stressors change soil status in Tahoe basin watersheds to assist forest managers in preparing management plans and make predictions about ecosystem response to natural (e.g., fire, insect attack, drought, or erosion) and anthropogenic (e.g., air pollution, harvesting, development, or climate change) perturbations. For example, a comprehensive assessment of the effects of both wildfire and prescribed fire and postfire vegetation on long-term response in biological and physicochemical soil parameters is needed to better understand fire and its role in restoration ecology.

Knowledge advancement potential**—**Because regulatory policy is often based on the subjective judgment of "risk potential" rather than on a sound quantitative decision support system, the application of predictive models can provide important tools to understanding and estimating the potential outcome of management strategies and programs. Successful model application, however, is accomplished through site-specific parameterization and model calibration. Establishing the means for prioritization of which ecosystem parameters are important, what should be measured, and what information is needed to parameterize and calibrate the models is recommended. In the event that the current models are not adequate predictors, appropriate modifications or adjustments are needed to make the existing models more functional. If this is not an option, starting from scratch and developing a new model that is simple, accurate, and appropriate for the Tahoe basin may be necessary. Model use and predictive application is recommended to enable consistency among agencies basinwide wherein the acquisition of a more robust quantitative database could provide the foundation for policies of future management strategies.

- Effects of climate change as related to soil conservation:
  - There is concern that anthropogenic activities over the last century have resulted in nontypical ecosystem structure throughout the basin of which the distribution, character, variability, and potential response to climate change have not been evaluated. Consequently, strategic efforts directed toward long-term site restoration in response to a quasi-natural state will be the more likely scenario. Quantitative assessment of what we can and cannot hope to accomplish on a long-term basis is recommended.
  - More comprehensive localized point source precipitation, surface runoff, erosion, and nutrient transport data is recommended to quantify potential discharge loads as a function of amount, type (snow vs. rainfall), frequency, and precipitation intensity. It is recommended that research and monitoring projects be designed to address potential changes in hydrologic parameters as a result of climate change.
  - Investigate the implications of climate change on slope stability parameters. It is recommended that surface soil stability, compaction, soil structure and aggregate stability, infiltrability and runoff, and potential for mass wasting all be tested under scenarios of different temperature and moisture regimes to estimate the potential effects of climate change on soil erosion in the Lake Tahoe basin.

Knowledge advancement potential—The implications associated with climate change cannot be ignored. Predictions for changes in precipitation quantity and intensity are quite variable for the Sierra Nevada. One scenario is that precipitation will increase in intensity leading to large-scale flooding. Another is that the Lake Tahoe area will be subject to overall warmer temperatures and more evapotranspiration, while increased precipitation will be more common farther to the north. There is general agreement, however, that with warmer temperatures snow elevation levels will be higher and accumulation likely lower, which will lead to longer fire seasons. Examination of management strategies involving biomass reduction, drainage control, and practices to diminish sediment and nutrient transport to Lake Tahoe is recommended in the context of shifting the quality and amount of hydrologic input. Such an examination will likely necessitate new approaches. It is recommended that future planning for the production of resilient, spatially heterogeneous and diverse forest structure be designed to account for potential changes in hydrologic function in response to different moisture regimes to determine what the ultimate effects of climate change could be on management protocols for sensitive areas at the watershed and local scales.

- Policy implications and adaptive management strategies as related to soil conservation:
  - Monitor and study established environmental thresholds for attainment and performance effectiveness. It is recommended that regulatory agencies and land managers develop a protocol for periodic review, verification, and update of processes, quantitative thresholds, and policy relevance. More research and monitoring of existing regulatory programs is recommended, such that their overall effectiveness and applicability can be more quantitatively assessed relative to their actual reduction of nutrient and sediment loading to the lake, and the subsequent enhancement of water clarity. Develop a basinwide protocol for "standard methods of ecological measurement and monitoring in the Tahoe basin."
  - Continued research that addresses critical natural resource issues and critical management questions relevant to soil conservation in the Tahoe Basin is essential. This exercise can begin by identifying a list of agency-specific management questions pertinent to soil conservation relative to key soil properties and conditions of interest. For example, what are the appropriate management strategies that maximize defensible space (measures taken to protect homes from wildfire, e.g., removing vegetation), but at the same time function to minimize erosion and the degradation of runoff water quality? It is then important to take advantage of unique opportunities and small-scale experimental field trials to quantitatively evaluate potential impacts. To ensure credibility and applicability, such research would make every effort to be scientifically defensible, applicable to the Tahoe basin or similar ecological settings, and publishable in peer-reviewed journals.
  - Restoration and BMP strategies are generally implemented to mitigate known adverse impacts from either natural events or anthropogenic

activities. Choosing the most effective strategy therefore necessitates a thorough knowledge of the mitigation objective, process mechanics, both short- and long-term functionality, and whether or not these components will differ depending on location within a given watershed or the Tahoe basin in general. Performance evaluation is commonly assessed on a collective (e.g., projectwide) rather than individual (e.g., specific management activity) process basis. Complete evaluation of which strategies are truly the most effective in meeting specific restoration objectives would require testing each management activity against one another as well as assessing their cumulative effects. Management strategies implemented for one purpose (e.g., defensible space) may or may not have an effect on other issues of concern and ascertaining why some work better than others in one locale vs. another (or not at all) is a critical issue.

Knowledge advancement potential—If greater confidence in performance effectiveness can be developed, consistency will likely follow. With new technology comes the opportunity for innovative soil conservation strategies that could alter or refine historical threshold values. In the past, technological advancement and expansion of the knowledge base was much slower. Today, it is not unusual for substantial new advancements to take place on a 5-year rather than a 25-year cycle. Key to the success of any such approach, however, is the development of a consistent and effective monitoring protocol for key soil properties and conditions that is current, process-specific, and uniform across agencies and contractors. Hence, research is recommended to develop a standard protocol for ecological measurement and monitoring in the Lake Tahoe basin, which includes variable levels of intensity that can be applied to different types and scale of projects. In its absence, implementers and agencies frequently employ different techniques in attempting to evaluate the performance effectiveness of similar soil conservation activities. Comparative interpretive assessment is then difficult to impossible. Furthermore, evaluating which conservation and/or restoration methods are most effective is recommended in the context of a more comprehensive framework wherein each on-the-ground management strategy could be tested against one another in similar and divergent environments. Therein lay key opportunities where new and unique soil conservation strategies could be explored. Finally, agency representatives can clearly identify agency-specific areas of concern, and then work with scientists and implementers to articulate the respective critical soil conservation issues. This would greatly assist in the development and design of successful monitoring, opportunistic, and/or experimental research programs that generate data and information directly applicable to agency needs.

Ecology and Biodiversity

The integrity of animal and plant communities serves as a critical measure of the effectiveness of implementation policies designed to protect and restore ecosystem processes in the Lake Tahoe basin. The conservation of plants and animals in the Tahoe basin is wholly dependent on the conservation of its terrestrial and aquatic ecosystems. Thus, the research agenda for biological diversity and ecological function is based on investigations that integrate data collection efforts across scientific disciplines to maximize the recovery and persistence of biological diversity. The Ecology and Biodiversity research strategy in chapter 6 highlights the interactions between native species and communities, and natural and human-caused stressors that present the greatest ecological and social risk, and for which research can reduce uncertainties presenting barriers to more effective management. Near-term ecology and biodiversity research priorities include:

- **Old-growth and landscape resilience**: The ultimate objective of forest management is to restore and maintain forest health and resilience such that forests and their associated biota are able to maintain the full range of functions, their native biological diversity, and continues to perform the ecosystem services upon which human communities in the basin depend. The primary uncertainty limiting management's ability to meet this objective is a clear understanding of what environmental conditions to create, and when and where to create them. Specific questions pertain to the historical amount and distribution of forest structural conditions, associated plant and animal species composition, and how to translate historical conditions into target conditions for the future that will enable forested ecosystems to adapt to future environmental stressors without the loss of function or biological diversity. Old forests are of particular concern and interest, since despite the maturity of existing forests, it is apparent that extant forests have lost ecological complexity associated with old forests, and therefore species and functions restricted to old forests are rare and most at risk from uninformed management. Finally, robust measures of forest biological diversity and resilience are recommended to enable simple and effective tracking of management progress and success.

- **Fire regime**: One of the greatest ecological risks associated with fire is the uncertainty associated with the effects of fuel reduction treatments—both their effectiveness in changing fire behavior, and the consequences of treatment effects on other ecological conditions, such as biological diversity and forest ecosystem resilience. The near-term research priorities pertain to addressing risks and uncertainties posed by current management activities, which target fuel reduction treatments on thousands of acres without an indepth understanding of the ecological consequences. Therefore, near-term research priorities include improving the understanding of the effects of various types and intensities of treatments on the spectrum of ecosystem management objectives, including but not restricted to fire behavior. Of primary concern is the fate of terrestrial species and processes, as they are directly affected by forest conditions. It would be most efficient to develop and test silvicultural prescriptions in the course of addressing near-term research priorities, as opposed to after ecological risks are more clearly understood. Once the primary ecological objectives at risk as a function of reducing the threat of catastrophic wildfire are understood, it is important to develop simple and informative measures of their status for long-term monitoring.

- **Special communities**: The conservation and restoration of special communities in the basin all rely on similar information: (1) maps of current location and condition throughout the basin, (2) reference conditions based on historical data and other relevant data sources, (3) evaluation of the effectiveness of restoration approaches, and (4) the development of performance measures to assess status and restoration effects. A few unique information needs are associated with individual special communities. In aspen communities, techniques for converting conifer-encroached stands back to aspen-dominated habitats is a primary information need. Fens and meadows are under an unknown level of threat from various human activities. The current status of marshes is basic information that is lacking. Finally, detailed information on genetic and environmental sensitivities of Tahoe yellow cress are needed to aid population restoration efforts of this endemic species.
- **Aquatic ecosystems**: The emphasis of aquatic ecosystem research is on conservation and restoration of vertebrate biota in Lake Tahoe and the conservation of species in the rich array of other aquatic ecosystems around the basin. In Lake Tahoe, the uncertainties with the greatest potential impact on management are those associated with the interactions between nonnative and native plant and animal species. These interactions have potential consequences for biodiversity, lake clarity, and near-shore aesthetics. Research on measures to control established nonnative species is recommended. This research is best pursued through an adaptive management approach, where

information from scientific assessments of pilot projects is used to guide longer-term management strategies. Restoration of native fishes in Lake Tahoe presents a steep challenge, and information on the ecological interactions is key to making progress. The other aquatic ecosystems are in need of more basic information, namely the status of vertebrate populations and communities, and factors limiting the ability of sites to support native species. Once these things are better understood, the development of efficient measures that can be used to track conditions over time is recommended.

- **Urban ecosystems**: Research recently conducted in the Lake Tahoe basin identified substantial and unexpected effects of urban development and human activities on various elements of biological diversity. The patterns observed varied by taxonomic group (i.e., birds, small mammals, mammalian carnivores, ants, and plants), among species (some were sensitive while others were not), and by type of human disturbance (e.g., habitat loss, habitat alteration, habitat enrichment, or different types of human activities). The results of that work suggest the need to understand mechanisms of key responses such that development and management can be conducted in a manner that minimizes and/or mitigates negative effects on biological diversity. Questions of particular priority pertain to better understanding thresholds of change in habitat loss, habitat alteration, or habitat use indicated by past research, specifically changes observed at 30 to 40 percent development. Above this threshold, it is unclear what happens, but sites likely become sinks, traps, or abandoned by a wide array of species. In addition to site-scale mechanisms, landscape-wide modeling is recommended to understand the implications of existing results and facilitate the rapid evaluation of the implications of new information on landscape design and management priorities. Finally, as in other subthemes, as vulnerable species and target ecological objectives in more urban areas are clarified, development and testing of effective measures are recommended for use in monitoring and assessment.

- **Recreation**: Recreational uses have been identified to have substantial effects on the occupancy and abundance of many and diverse species based on multiple research projects. Alternatively, species thought to be impacted by certain recreational activities (e.g., effects of off-highway vehicle use on occurrence of American marten) did not exhibit negative responses. Specific uncertainties in the Tahoe basin pertain to the effects of dogs on retaining biological diversity in more urban environments, and the effects of ski areas on montane obligates, namely American marten. Although population sizes of northern goshawk and bald eagle are limited, their sensitivity to the presence of people has important implications for the management of events and on-going recreational uses in the vicinity of known use sites. Effective measures of use and effects are lacking and their development will be important for monitoring.

- **Climate change**: Climate change is perhaps the ultimate source of uncertainty, and arguably poses a high environmental and economic risk. Under such circumstances, information needs start at the basics. In the case of ecological elements and processes, this translates to applying existing and new information to modeling potential responses—plant and animal ranges and associated effects on population sizes, species interactions, and ecological services—to predicted or potential climate change and associated broad-scale environmental responses. It is important for modeling to be conducted in the basin, as opposed to relying on modeling outside the basin or at larger scales because detailed information will be needed to inform how management can respond to potential threats. As with all other subtheme areas, as information is accrued, effective and reliable measures of key population and community metrics are recommended to be developed for monitoring.

Integrating the Social Sciences in Research Planning

The evaluation of social science research needs was included in this science plan to explicitly recognize that the processes underlying environmental degradation, as well as their conservation and recovery, are fundamentally based on human decisionmaking. Effective conservation and restoration policies rely on a well-grounded understanding of human behavior, the interaction of social and natural processes, and linking information from the social sciences to decisionmaking. The goals of the research strategy in chapter 7 are to (1) identify social science data and research needs for management objectives that are not directly environmental, (2) describe the research needs necessary to improve policy design and implementation for managing environmental conditions, and (3) develop a framework for prioritizing social science research needs in areas that focus on the interaction between the human and natural environments. Near-term recommended social sciences research priorities include:

- Recreation:
  - Develop a consistent, basinwide 3-year recreational survey cycle to track seasonal changes, crowding behavior, and long-term patterns of recreational activity change.

    - Statistical analysis of the factors associated with recreational quality in order to determine visitor preference and direct future infrastructure investment.
    - Analysis of recreational capacity in terms of ecological impact and infrastructure at both the specific site level and basinwide.

- Transportation:
    - Collection and analysis of current bicycle use data in order to determine road and trail use, and to determine adequacy of current bicycle routes and the potential for use as an alternative transportation mode.
    - Collection and analysis of public transit ridership data to and within the basin.
    - Centralized collection, inventory and distribution of transportation data at a basin level.
    - Develop a centralized Web-based information source about all basin-level public transportation systems.
    - Analysis of effective policy options for addressing parking in high-impact areas.
    - Predictive modeling on vehicle use, transit ridership, demographics, and linkages between economic health and emergency preparedness.

- Economics:
    - Increased data collection and analysis of housing trends at the community and basin level.
    - Increased data collection and analysis of employment trends at the community and basin level.
    - Increased data collection and analysis of tourism trends at the community and basin level.
    - Estimate affordable housing availability for year-round residents, public sector employees and workers in service and hospitality industry.
    - Evaluation, prioritization and coordination of Tahoe basin environmental improvement projects.
    - Development of community sustainability and well-being indicators.
    - Program evaluation of the effectiveness and cost-efficiency of existing policies.
    - Analysis of effective policy options for increasing affordable housing options.

- Scenic resources:
  - Examination of public perceptions of the scenic quality of natural and built environments.
  - Development of new TRPA Scenic Quality indicators.
  - Analysis of effective policy options for increasing building design diversity.
  - Analysis of effective policy options for improving overall scenic quality.
- Noise:
  - Increasing spatial and temporal monitoring to capture single-event noise levels.
  - Research on public acceptability and perception of current noise levels.
- Collaborative information management:
  - Information synthesis and knowledge-sharing about effective approaches for recreation infrastructure, and about mitigating environmental impacts in other alpine resort communities.
- Tahoe basin community management:
  - Consolidation of existing information, design of new collection instruments, and examination of methods for upscaling data to the Tahoe basin level and/or downscaling to the community level.
- Program design, policy evaluation, and policy process evaluation:
  - Develop policy conflict resolution mechanisms for programs working at cross purposes. Target research on policy evaluation and program design of costly programs.
- Fire and natural hazards:
  - Develop a basinwide emergency communications network, implement reforms to fuels management on private parcels, and begin extensive inter-agency review of basinwide coordination of fuels management.
- Climate change:
  - Develop predictive models of climate change impacts on the Tahoe environment. Focus on outputs that can communicate potential outcomes to local government, the general public, and agency personnel.

Those reading multiple chapters of this science plan will soon realize the research strategies differ in scope and breadth. These differences are due to the diversity of management issues that exist among the theme areas and to variations in the state of knowledge. Past efforts to obtain knowledge in each of the theme areas have not been equal. This means different levels of investment are needed to progress from this point forward. For example, we now have an operating Lake Tahoe clarity model that can be used to predict future conditions and analyze the effects of alternative management strategies aimed at improving Lake Tahoe water clarity. Thus, some research needs identified in the "Water Quality" research strategy will include recommendations to improve the validity and predictive capabilities of this model. In contrast, we are struggling to obtain and aggregate basic regional socioeconomic data for the Lake Tahoe basin that can inform us about trends in the human environment. These differences in knowledge base compromise our ability to understand and quantify interactions among resources, habitats, processes, and stressors. Continued commitment of future resources and funding across all five theme areas is recommended as the best strategy to even out the disparity in our knowledge base.

The near-term research priorities presented in the research strategies and above are based on the input of agency and stakeholder representatives received during subtheme identification, as well as the best professional judgment of the authors. Several factors (e.g., changing agency priorities, funding levels, the emergence of new issues or new information, and the availability of new technologies) can simultaneously affect the applicability of chosen research priorities. Thus, the selected priorities are best reviewed and revised regularly to ensure the current science needs and priorities reflect the changing information needs and evolving priorities of agencies charged with the welfare of the Lake Tahoe basin. For this reason, this science plan is considered a living document. The agency, stakeholder, and science community representatives active in the Lake Tahoe basin all share the continuing responsibility to revisit and update this document in the future.

Each research strategy is meant to serve as a stand-alone document. We think this organizational approach is most useful because government agency representatives and stakeholders often seek issue-specific information. This organizational approach also should aid those agencies dealing with multiple theme areas, because they are organized in distinct programs that generally coincide with the theme areas. However, this stand-alone approach affected the way cross-cutting issues are treated. In preparing this science plan, several issues that cut across multiple theme areas were identified:

- Quantification of key environmental indicators
- Model application and development
- Adaptive management functionality and effectiveness
- Research and policy implementation
- Effects of climate change
- Effects of fire

The stand-alone organization of the research strategies means information on cross-cutting issues is presented in multiple chapters. For example, those wanting to learn about the research recommended to improve our understanding of climate change effects will need to review the appropriate section in several research strategies. Although this organizational approach means the reader will have to do more work to synthesize information on cross-cutting issues, this approach does allow for better integration of cross-cutting issues within each research strategy.

The target audience for information presented in this document includes those individuals within government agencies and the stakeholder community that have a role in the protection and management of the Lake Tahoe basin ecosystem. We hope this document is of particular use to those individuals who find themselves responsible for deciding if and how new funding for science should be allocated.

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Chapter 1: Overview[1]

Zachary P. Hymanson[2]

Introduction

A complex suite of interrelated changes has occurred in and around the Lake Tahoe basin over the last 150 years. These changes have substantially affected the atmospheric, aquatic, and terrestrial environments, as well as socioeconomic conditions in the basin (Elliott-Fisk et al. 1996, Lindström et al. 2000). Human responses to these changes have taken many forms; however, the overall trend shows a transition from policies favoring unrestricted use of habitats and living resources for development and economic benefit, to policies favoring limitations on development and increased habitat conservation and restoration (see Elliott-Fisk et al. 1996 for a review). This transition ultimately led to the policy declaration establishing the Tahoe Region Planning Compact (Public Law 96-551), which aims to ensure equilibrium between the region's natural endowment and its human-developed environment, and to the subsequent state of California designation of Lake Tahoe as an Outstanding National Resource Water under the Federal Clean Water Act (LRWQCB 1995).

The known effects of past actions and the unique character of the Lake Tahoe basin have led to broad-based support for substantive conservation and restoration efforts over the last two decades (CTC 2006, Elliott-Fisk et al. 1996, Murphy and Knopp 2000, U.S. Public Law 106-506 2000, TRPA 2001). Increased attention and funding over the past decade, in particular, have resulted in remarkable progress toward restoration goals, along with considerable information on the strengths and weaknesses of different approaches to addressing the substantial restoration challenges (Elliott-Fisk et al. 1996; Murphy and Knopp 2000; TRPA 2002, 2007). Restoration has focused not only on Lake Tahoe, but also on the entire watershed. Special attention has been given to the highly interdependent nature of terrestrial and aquatic habitats, and the multifaceted socioeconomic conditions that influence the Tahoe basin ecosystem (Elliott-Fisk et al. 1996, Murphy et al. 2000). The Lake Tahoe basin is recognized as a highly complex physical, biological and social environment, and the challenges posed by its restoration and continued management for multiple benefits are paralleled by few other locations.

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[2] Tahoe Science Consortium, Incline Village, NV 89451.

Conservation and restoration of the Lake Tahoe basin ecosystem have required the sustained engagement of federal, state and local governments, as well as the private sector. These entities have worked together to develop and implement a variety of programs and activities aimed at achieving common environmental and social goals (TRPA 2001, 2007). Yet determining how to proceed with conservation and restoration efforts in the face of limited information remains a central challenge to these efforts. Science (e.g., monitoring, research, and modeling), particularly applied science completed to inform adaptive management, provides a promising set of tools to address information limitations that affect our ability to select and implement effective management strategies. The coordination of scientific activities with management actions is at the core of an effective adaptive management approach (Manley et al. 2000). However, effort is required to organize and describe the science activities needed to inform an adaptive management system focusing on the conservation and restoration of a complex system. This document presents the results of science community efforts to organize and describe the initial elements of an integrated science plan for the Lake Tahoe basin: a conceptual framework for science operating in an adaptive management system, and focused research strategies covering topic areas of relevance to Tahoe basin management and conservation. Separate, agency-led efforts are underway to develop other essential elements of an integrated science plan, including programs for status and trends and effectiveness monitoring, new data applications aimed at converting data into information and knowledge, and the integration of monitoring and applied research efforts.

Approach for Developing This Science Plan

This science plan was developed through a collaborative effort among agency, science community, and stakeholder representatives to identify and refine science information needs for the Lake Tahoe basin. The main purpose of this effort was to develop a set of research strategies to address key uncertainties and information gaps that challenge resource management and regulatory agencies. The research needs identified in these strategies are based on assessments of the issues and information needs that currently confront government agencies and stakeholders working in the basin. The resulting strategies are intended to guide future research efforts and to help maximize the information gained from future science investments.

The plan begins by presenting an overview of a conceptual model and framework that identify issues of concern in the Tahoe basin and describe how science can work to inform polices, management strategies, and actions within the context of a Lake Tahoe basin adaptive management process. Next, the plan presents five chapters describing focused research strategies for the theme areas of (1) air quality, (2) water quality, (3) soil conservation, (4) ecology and biodiversity, and (5) integrating the social sciences in research planning. Each research strategy describes the knowledge gaps and research needs for relevant issues of concern (i.e., subthemes). Scientists worked with resource management agency representatives and stakeholders to identify relevant subthemes (e.g., fire and fuels management is one subtheme under the Ecology and Biodiversity theme area), and to identify the management issues and information needs associated with each subtheme (e.g., minimizing adverse impacts to wildlife is one management issue under the fire and fuels management subtheme). For each subtheme, the authors summarize the current state of knowledge, identify remaining uncertainties and knowledge gaps, and list science activities that address the uncertainties and knowledge gaps.

The research strategy theme areas were chosen based on an examination of resource areas considered in four management plans or planning processes: (1) the 1987 Lake Tahoe Basin Regional Plan, (2) the 2000 Lake Tahoe Watershed Assessment, (3) the Pathway planning process,[3] and (4) update of the Environmental Improvement Program for the Lake Tahoe basin (table 1.1).

Three common needs drive the recommendations presented in each research strategy:

- Increasing our understanding of the factors and processes driving change.
- Developing the tools and understanding to predict future conditions in the Lake Tahoe basin and permit comparisons among alternative futures.
- Providing information to inform future management decisions aimed at conserving and restoring the natural and human environments of the Lake Tahoe basin.

Each research strategy concludes with a presentation of near-term research priorities. Near-term research priorities are based on input received from agency and stakeholder representatives during subtheme identification, as well as the best professional judgment of the authors. Several factors (e.g., changing agency priorities, funding levels, the emergence of new issues or new information, and

[3] The Pathway planning process (formerly known as Pathway 2007) is a collaborative planning effort among four partner agencies, including the Tahoe Regional Planning Agency, USDA Forest Service, the California Lahontan Regional Water Quality Control Board, and the Nevada Division of Environmental Protection. These agencies are working together to update important resource management plans for the Lake Tahoe basin, which will guide land management, resource management, and environmental regulations over the next 20 years. This planning process is ongoing and is referred to as "Pathway" or "Pathway planning process" in this document. More information about the Pathway planning process is available at http://www.pathway2007.org/.

Table 1.1—A comparison among theme areas considered in four Lake Tahoe basin planning documents or processes and the Lake Tahoe Science Plan

TRPA 1987 Regional Plan: threshold categories	2000 Lake Tahoe watershed assessment	Pathway planning process	Environmental Improvement Program—update	Lake Tahoe science plan theme areas
Air quality[a]	Air quality	Air quality	Improving air quality and transportation	Air quality
Soil conservation/ stream environment zone (SEZ)	Upland water quality/ sediment and nutrient discharge	Soil conservation and SEZ habitats	Habitat and vegetation	Soil conservation
Water quality[a]	Water quality	Water quality	Storm water management	Water quality
Vegetation[a]	Biological integrity and aquatic resources (Vegetation, Wildlife, Fisheries)	Vegetation and forest fuels	(1) Forest health and fuels management (2) Habitat and vegetation	Ecology and biodiversity
Wildlife[a]		Wildlife and fisheries	(1) Habitat and vegetation (2) Watershed management (3) Threatened, endangered, and sensitive species	
Fisheries				
—	Socioeconomics (—, Recreation)	Socioeconomics	—	Integrating the social sciences in research planning
Recreation		Recreation	Enhancing recreation and scenic resources	
—	—	Transportation	Improving air quality and transportation	
Scenic resources		Scenic quality and resources	Enhancing recreation and scenic resources	
Noise	—	Noise	—	
—	Adaptive management strategy	Lake Tahoe adaptive management system	Program support and applied science program	Science plan framework and overview conceptual model

[a] Theme areas considered in the June 6, 2001, key management questions. See "A Review of Science Planning and Support in the Lake Tahoe Basin" below for more information about development of the key management questions.
— = not applicable, TRPA = Tahoe Regional Planning Agency.

the availability of new technologies) can simultaneously affect the applicability of chosen research priorities. Thus, the selected priorities are best reviewed and revised regularly to ensure the current science needs and priorities reflect the changing information needs and evolving priorities of agencies charged with the welfare of the Lake Tahoe basin. For this reason, this science plan is considered a living document. The agency, stakeholder, and science community representatives active in the Lake Tahoe basin all share the continuing responsibility to revisit and update this document in the future.

A Review of Science Planning and Support in the Lake Tahoe Basin

Over the last 30 years, there have been several efforts to organize and describe the science needed to improve our understanding of the Lake Tahoe basin ecosystem and inform management actions. The most substantial efforts include the following:[4]

- Research Needs for the Lake Tahoe Basin (LTARCB 1974). A National Science Foundation funded project, which aimed to "encourage research needed to achieve the planning and management objectives of public and private entities" and to "provide scientific expertise and data to support effective planning and management programs." Information shortfalls that compromised management of the Tahoe basin's air, water, vegetation, fish and wildlife, social sciences, and resource systems were identified. More than 80 separate research needs were proposed.
- Lake Tahoe Environmental Assessment (WFRC IRTF1979). The compilation and analysis of information prepared in support of this assessment evaluated data for a number of resources, habitats, and socioeconomic factors. These were pivotal evaluations formally introducing the concepts of carrying capacity and environmental thresholds, which were central to the scientific underpinnings of the 1987 Lake Tahoe Basin Regional Plan.
- Lake Tahoe Case Study (Elliott-Fisk et al. 1996). This document took a science-based approach to provide an ecosystem and policy assessment of the Lake Tahoe basin. The case study synthesized information from these assessments to inform the Sierra Nevada Ecosystem Project, and identified future science-based management needs for the Lake Tahoe basin.
- Environmental Improvement Program (EIP) (TRPA 2001). The EIP described a series of program areas and projects, which if implemented, would advance the Lake Tahoe basin toward attainment of the environmental thresholds identified in the 1987 Lake Tahoe Basin Regional Plan. The science and research portion of the EIP (updated and expanded in 2001) identified threshold and EIP-related research and monitoring projects designed to (1) advance scientific understanding of ecosystem processes and threshold attainment, (2) refine planning and restoration strategies, and (3) improve and quantify the effectiveness of capital improvement projects.

[4] Information on science planning is taken in part from Murphy (2000).

- Lake Tahoe Watershed Assessment (Murphy and Knopp 2000). This document provided a synthesis of 20 years of research publications and reports dealing with the atmospheric, aquatic, and terrestrial environments; the living resources associated with these environments; and socioeconomic conditions. Like the documents that precede it, this assessment included recommendations for research and monitoring. The assessment also presented an adaptive management strategy, describing a means of organizing current information, and linking management planning with essential science activities.
- Key Management Questions (SAG 2001). Scientists and agency representatives worked together to develop a list of Key Management Questions (KMQ) to direct new research and monitoring efforts in the Lake Tahoe basin. Some of the KMQs were periodically revised and updated (2002–04) to reflect the most important questions that land managers, project implementers, and regulators had about land use decisions and methods to improve ecosystem health in the Lake Tahoe basin. Tahoe basin agency executives prioritized some of the KMQs. This information was used by federal and state agencies to develop budgets for future science funding.

The documents described above range from lists of research needs and questions to indepth reviews and issue-specific analyses. In some cases, the documents also describe processes and approaches for obtaining new scientific information. To varying degrees, all of these efforts provided recommendations for the kinds of science activities, and in several cases, the specific studies needed to address existing uncertainties and information gaps.

In several cases, it was implicitly assumed that providing a description of the science needs for the Lake Tahoe basin would lead to establishment of a sustained program for addressing those needs. However, such a program has never been established and, with the exception of water quality, information gains for many critical issue areas generally lag behind the information needs of managers and policymakers. In some cases, these information gains are lacking because the necessary studies have not been initiated or completed. In other cases, these information gains have not been realized because of a lack of synthesis and analysis of existing data.

With the exception of the KMQs, none of the science plans prepared for the Lake Tahoe basin have been supported by sustained science planning processes that provide a means for objective prioritization and regular revision. Unfortunately, the KMQ planning process eventually fragmented with different issue areas receiving varying degrees of attention. Functional science planning processes are critical to ensuring that a science program remains relevant and responsive to management information needs. Support for science planning also is needed to ensure that any funds available for new science address the highest priority information needs.

In addition to efforts to organize and describe science needs, other efforts have improved the organization of science entities and implementation of science activities in the Tahoe basin. A persistent challenge has provided the motivation to improve science organization and implementation:[5]

> For years the academic and management communities could not agree on a scientific agenda that would answer both key management and research questions. Many times, scientific work was not deemed pertinent to what the agencies wanted, and the management questions were not articulated in ways the science community could use.

Explicit efforts to address this challenge were formalized in 1999 with the signing of a memorandum of understanding (MOU) with a primary focus on priority research, monitoring, evaluation, and outreach supporting Tahoe basin management goals. The entities signing this MOU (Tahoe Regional Planning Agency [TRPA], University of Nevada, Reno [UNR], Desert Research Institute [DRI], University of California, Davis [UCD], U.S. Department of the Interior, Geological Survey [USGS], and the U.S. Department of Agriculture, Forest Service [USFS]) committed to work collaboratively to:

- Establish a joint steering committee to evaluate the EIP to determine what environmental issues may benefit from broader research inquiry.
- Further develop and improve the communication and coordination among existing research groups working in the Tahoe basin to prevent duplication of efforts and provide the maximum interdisciplinary teamwork necessary to resolve the most important environmental issues.
- Contribute to TRPA's development of a research master plan and set of guiding principles for research inquiry in the Lake Tahoe Region related to priority preservation, restoration, and enhancement needs.
- Encourage the development of competitive research proposals with peer review to achieve the highest caliber of scientific assessment of problems facing the Lake Tahoe region.
- Identify monitoring tasks and evaluations that would be assured continuance to fully inform the research community evaluating the Lake Tahoe region.

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[5] York, T. 2008. Personal communication. Environmental scientist. California Tahoe Conservancy, 1061 Third Street, South Lake Tahoe, CA 96150.

- Develop outreach plans to convey research results and options to the public in general and specifically to the communities within the Lake Tahoe region.

In 2000, the TRPA requested the MOU participants convene a Lake Tahoe Science Advisory Group (SAG). The SAG also included representatives from numerous state, federal, and local agencies. Key objectives of the SAG were to (1) develop a scientific work plan that would dovetail with restoration efforts and management objectives and (2) coordinate/facilitate the operating principles of a Tahoe Environmental Science System identified in a second MOU signed in February 2000. The SAG, in conjunction with a number of work groups active in the Tahoe basin, identified critical information needs requiring attention for effective management decisions. This was intended to be an ongoing process that included two key components: (1) development of a series of KMQs, and (2) development of a science plan, produced by the research institutions, which addressed the KMQs. Although the SAG did prepare KMQs for a number of theme areas (table 1.1 and summarized above), funding and resource commitments to produce a science plan did not occur.

Over time, support and commitment to the SAG and its goals declined. Select agencies did pursue new funding initiatives to support scientific investigations related to specific agency needs (e.g., technical studies for the Lake Tahoe total maximum daily load, and the Lake Tahoe Air Deposition Study). However, with the exception of water quality studies, efforts to organize collaborative science efforts within and among issue areas continued to struggle.

In 2003, the federal government began providing funding to support implementation of the Lake Tahoe Restoration Act (U.S. PL 106-506 2000). Some of this funding was reserved for new science; however, the persistent challenge identified above continued to compromise the processes for identifying science needs and the objective selection of projects for funding. In addition, all parties recognized that the SAG had neither the charge nor the resources to develop a vision, structure, and program capable of supporting science and research as it applies to Lake Tahoe basin restoration (TRPA and USCOE 2005). Thus, discussions were initiated in December 2003 among members of the science community and staff from the TRPA, the U.S. Environmental Protection Agency, and the U.S. Army Corps of Engineers to evaluate and possibly restructure SAG operations to better support allocation of federal funding under the Lake Tahoe Restoration Act. These discussions led to a proposal for an enhanced science community group known as the Tahoe Science Consortium (TSC). In 2005, science community and agency representatives signed an MOU forming the TSC,[6] and establishing its primary objective: "To provide environmental managers and decision makers with comprehensive and well-synthesized scientific findings drawn from research, monitoring, and modeling." The TSC is a partnership among five research organizations: (1) UNR; (2) UCD; (3) DRI; (4) the USFS, Pacific Southwest Research Station, and (5) the USGS, Carson Science Center. The TSC operates independently of the management and regulatory agencies working in the Tahoe basin, and TSC efforts have focused on:

- Science planning: Working with Lake Tahoe basin agency representatives to develop regional monitoring approaches for specific issue areas, and developing a science plan for the Lake Tahoe basin that identifies and prioritizes research needs. These efforts are intended to contribute to the primary objective of the TSC.
- Peer review: Administering or conducting the scientific peer review of research proposals, science products, or technical programs related to Lake Tahoe basin management and restoration. Independent peer review is intended to ensure that science activities conducted in the basin are scientifically sound, and that the results are technically credible.
- Technical assistance: Providing scientific input and technical advice to resource management and regulatory agencies that addresses management issues and concerns as they arise.

After nearly a decade of effort, agency and science community representatives have made progress in addressing the persistent challenge affecting science organization and implementation. Formation of the TSC concurrently with increased investments and commitments by the TSC partners represents major efforts of the science community to better address Lake Tahoe basin science needs on a sustained basis. In addition, the establishment of two new working groups (the Tahoe Science Agency Coordination Committee, and the Science and Management Integration Team) has provided greater organizational capacity for agencies to communicate management issues and information needs to the science community, and to provide the ongoing support for science planning processes. Efforts now focus on sustaining progress.

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[6] More information about the TSC and its member organizations is available at http://www.tahoescience.org/.

Advancing an Applied Science Program in the Tahoe Basin

Clear policy direction and agency commitments are essential to advancing an effective science program. The Lake Tahoe Restoration Act (PL 106-506) sets forth the primary policy directive for providing and sustaining an effective science program in the Tahoe basin:

> The Secretary shall provide for continuous scientific research on and monitoring of the implementation of projects on the [EIP] priority list, including the status of the achievement and maintenance of environmental threshold carrying capacities.

This overarching policy directive is supported by several policies and goals within the TRPA (TRPA 1986) and through implementation of the Federal Vision for the EIP (Lake Tahoe Basin Executives 2006).

Fundamentally, science comprises several practices and principles, which are applied in an integrated fashion to provide objective and verifiable approaches to acquiring new information that addresses uncertainties and knowledge gaps. To effectively support the ongoing information needs of resource management and regulatory agencies, these practices and principles are best organized and implemented as an integrated science program that includes the means to provide timely information in formats useful to agency representatives and decisionmakers.

Conceptually, the efforts and activities of an integrated science program can be divided among three basic elements: (1) monitoring, (2) empirical research, and (3) data application. To be effective, however, efforts need to be integrated across all three elements, and the allocation of resources among all elements is essential. This is the basis for the conceptual framework presented in chapter 2.

The brief review of past science planning efforts presented previously shows that merely producing a science plan is not enough to ensure the establishment of a sustained science program that can deliver useful information covering a diversity of issues. Clear policy direction is essential, but a deeper level of commitment among all relevant parties would enhance progress from planning to implementation. An explicit assumption of this effort is that the agencies charged with responsibility for the welfare of the Lake Tahoe basin will work to establish the funding, resources, and infrastructure necessary for sustained implementation of an applied science program. The TSC is prepared to work with agency representatives to make a sustained science program for the Lake Tahoe basin a reality.

Geographic Scope and Environmental Setting[7]

Lake Tahoe and its tributary watersheds together make up the Lake Tahoe basin (fig. 1.1). In most cases, the Lake Tahoe basin encompasses the entire geographic scope of this science plan. Where appropriate, however, the scope is broadened to consider external factors (e.g., regional meteorology or climate change) that can substantially influence conditions or future management actions within the basin.

The Lake Tahoe basin lies in the east-central portion of the Sierra Nevada mountain range and on the western boundary of the Great Basin. It is a montane, lacusterine-dominated ecosystem with several physical characteristics that make it a unique feature of the Sierra Nevada mountain ecosystem (table 1.2).

The broad elevation range of the basin (1900 to 3050 m [6,200 to 10,000 ft] above sea level) and a topography that strongly controls precipitation and temperature combine to yield a wide diversity of montane vegetation types, ranging from coniferous forests and woodlands, riparian forests, subalpine to alpine meadows, various wetland communities, and Great Basin shrublands. Soils are thought to act as a secondary control (after climate) of vegetation patterns. Geology within the basin is dominated by granitic rocks and soils in the southern portions, with an overlay of volcanic rocks and soils in the northern portions. The diversity of plant communities and vegetation types creates a broad spectrum of wildlife habitats. Numerous fish and invertebrate species occupy the stream and lake habitats, but in many cases, introduced species dominate (Chandra 2003).

Human activities have had and continue to have a dominant influence on the natural resources and environment of the Lake Tahoe basin. These activities include numerous past and present habitat and species modifications (e.g., logging; urban, commercial, roads, and infrastructure development; recreation; fire suppression; water diversion; species extirpations and introductions; habitat enrichment; and habitat restoration). Most anthropogenic activities are considered stressors to the natural environment, so restoration projects generally aim to remove or reduce the effects of these stressors. Humans and their activities will remain dominant components in the Lake Tahoe basin ecosystem, so ensuring the equilibrium between the basin's natural endowment and its human-provided environment remains the primary directive.

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[7] Information on geographic scope and key physical characteristics is taken in part from Elliott-Fisk et al. (1996).

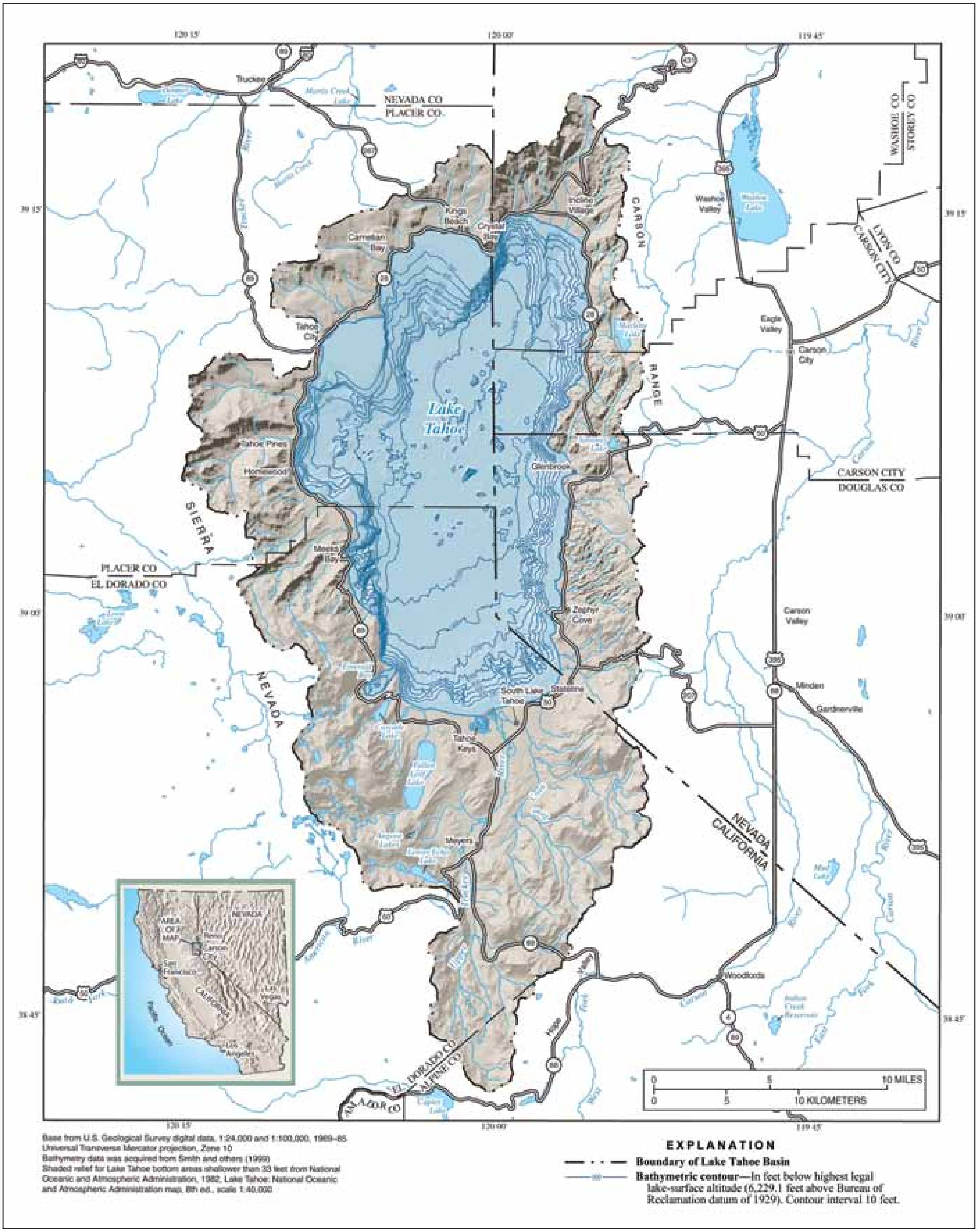

Figure 1.1—Plan view of the Lake Tahoe basin illustrating select hydrologic and bathymetric features, major roadways, and political boundaries. The area of shaded relief indicates the watershed boundary. Courtesy of the U.S. Geological Survey.

Table 1.2—Key physical characteristics of the Lake Tahoe basin

Characteristic	Size	Comment
Basin surface area	1300 km^2	
Land surface area	800 km^2	
Developed land surface area	83 km^2	The developed land area occupies about 10.5 percent of the total land area and includes residential, commercial, institutional, utilities, and transportation development.
Undeveloped land surface area	~717 km^2	The undeveloped land area occupies about 89.5 percent of the total land area. This area is dominated by undeveloped montane forest habitat.
Lake surface area	500 km^2	The lake surface area comprises about 38 percent of the basin surface area, yielding a watershed area to lake area ratio of ~1.6:1.
Maximum lake depth; mean lake depth	502 m; 313 m	Lake Tahoe is the 11^{th} deepest lake in the world.
Lake width and length	19 km × 35 km	
Lake volume	~156 km^3	The top 6 ft of Lake Tahoe is operated as a draw-down reservoir with a nominal yield of 903 million m^3.
Average water residence time	650 years	Average residence time of most pollutants of concern is on a decadal time scale or less.
Number of watersheds draining into Lake Tahoe	63	Tributary inflow annually delivers about 430 million m^3 to Lake Tahoe.
Number of drainages out of Lake Tahoe	1	The Truckee River flows northeast from Lake Tahoe to Pyramid Lake, Nevada.

Using This Document and Target Audience

This science plan includes six chapters that present a conceptual framework and focused research strategies for five topics of importance to the Lake Tahoe basin ecosystem. Chapter two presents the conceptual framework and overview conceptual model for this science plan. Further, the chapter describes the foundational elements and approach for establishing an integrated science program as part of a Lake Tahoe basin adaptive management system. The overview conceptual model will orient readers to the important issues covered in this plan and the relationships among those issues. Five theme-specific research strategies make up the core of this science plan. These chapters cover the topics of air quality, water quality, soil conservation, ecology and biodiversity, and integrating the social sciences in research planning.

The research strategies in this science plan differ in scope and breadth because of the diversity of management issues that exist among the theme areas and variations in the state of knowledge. Past efforts to obtain knowledge in each of the theme areas have not been equal (TRPA 2007), so different levels of investment are needed to progress. For example, we now have a Lake Tahoe clarity model that can be used to predict conditions and analyze the effects of alternative management strategies aimed at improving Lake Tahoe water clarity. Thus, some research needs identified in the "Water Quality" research strategy will include options for improving the validity and predictive capabilities of this model. In contrast, we are struggling to obtain and aggregate basic regional socioeconomic data for the Lake Tahoe basin that can inform us about trends in the human environment. These differences in knowledge base compromise our ability to understand and quantify interactions among resources, habitats, processes, and stressors. Continued commitment of future resources and funding across all five theme areas is believed to be the best strategy to even out the disparity in our knowledge base.

Each research strategy is meant to serve as a stand-alone document. We think this approach is most useful because government agency representatives and stakeholders often seek issue-specific information. This approach also should aid those agencies dealing with multiple theme areas, because they are internally organized across distinct programs that generally coincide with the different theme areas. However, this stand-alone approach affected the way cross-cutting issues are treated. Through the course of preparing this science plan, several issues that cut across multiple theme areas were identified:

- Quantification of key environmental indicators
- Model application and development
- Adaptive management functionality and effectiveness
- Research and policy implementation
- Effects of climate change
- Effects of fire

The stand-alone organization of the research strategies means information on cross-cutting issues is presented under multiple theme areas. For example, those wanting to learn about the research needed to improve our understanding of climate change effects will need to review the appropriate section in several chapters. Although this organizational approach means the reader will have to do more work to synthesize information on cross-cutting issues, this approach does allow for better integration of cross-cutting issues within each theme area.

The target audience for this document includes those individuals within government agencies and the stakeholder community that have a role in the protection and management of the Lake Tahoe basin ecosystem. We hope this document is of particular use to those individuals who find themselves responsible for deciding if and how new funding for science should be allocated.

English Equivalents

When you know:	Multiply by:	To get:
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles
Square meters (m^2)	10.76	Square feet
Square kilometers (km^2)	.386	Square miles
Cubic meters (m^3)	35.3	Cubic feet

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Chapter 2: Conceptual Framework for an Integrated Science Program[1]

Patricia N. Manley,[2] Dennis D. Murphy,[3] and Zachary P. Hymanson[4]

Introduction

Uncertainties always accompany the best efforts of environmental and resource managers. They are inescapable. Accordingly, many managers seek guidance from science to enhance the likelihood that their management actions and restoration efforts will meet desired objectives. Science to support land and resource management applies principles and practices in an integrated fashion to acquire objective and verifiable information to fill knowledge gaps, thereby reducing uncertainties. Scientific principles and practices employed to generate new information include the formulation of explicit hypotheses, application of the scientific method (the approach for designing experiments to test hypotheses), selection of methods to avoid bias (applying techniques that ensure independence and randomness), utilization of statistical analyses to transform data into information, and development of tools to transform information into knowledge. To support the information needs of land and resource managers and regulatory agencies, scientific activities are best organized and implemented through an integrated science program.

Conceptually, the activities carried out under an integrated science program that can serve to inform the management, conservation, and restoration of natural resources include three basic components—monitoring, research, and data application. Monitoring is used to establish baseline conditions, track management activities, and record outcomes. Empirical research seeks to elucidate cause-effect relationships, and in so doing enhances the understanding of ecosystem interactions and the effects of management actions in the context of natural environmental variation and anthropogenic influences. Data application includes a broad array of activities associated with handling data, including analysis and interpretation; modeling; data management; information dissemination; and knowledge application for assessment, evaluation, and decision support. This chapter provides more detail—including near-term priorities—for each component of an integrated

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science program. These descriptions are followed by a discussion of adaptive management, which describes how an integrated science program can help to inform and guide the management of complex systems. The chapter concludes with a section that introduces the reader to conceptual models: a tool used throughout this science plan.

Monitoring

Effective monitoring schemes are essential elements in integrated science programs. Monitoring results are often the main source of scientific information in support of adaptive management systems. Monitoring is a form of research and, like research, is best implemented in an experimental framework that differentiates between alternative explanations of how managed resources respond to environmental change. Monitoring has been defined as the "measurement of environmental characteristics over an extended period of time to determine status or trends in some aspect of environmental quality" (Suter 1993). In the Lake Tahoe Watershed Assessment, Manley et al. (2000) provided an expanded definition of monitoring, describing three forms of monitoring:

- **Implementation monitoring**—The monitoring of management actions in relation to planned activities. This form of monitoring catalogues the completion of projects or activities. It also documents compliance with environmental regulations and mitigation obligations in project implementation.
- **Effectiveness monitoring**—The monitoring of the effectiveness of management practices and actions in achieving desired conditions. This type of monitoring is recommended as an integral part of capital improvement, regulatory, and incentive programs (fig. 2.1), such that the outcomes of individual or combined effects of actions taken under various programs are known. Effectiveness monitoring does not address the uncertainties that are associated with techniques or designs, nor does it attempt to compare the relative effectiveness of different techniques or designs—these questions reside in the realm of empirical research. Integration of effectiveness monitoring and research to address priority uncertainties is the efficient and desired approach.

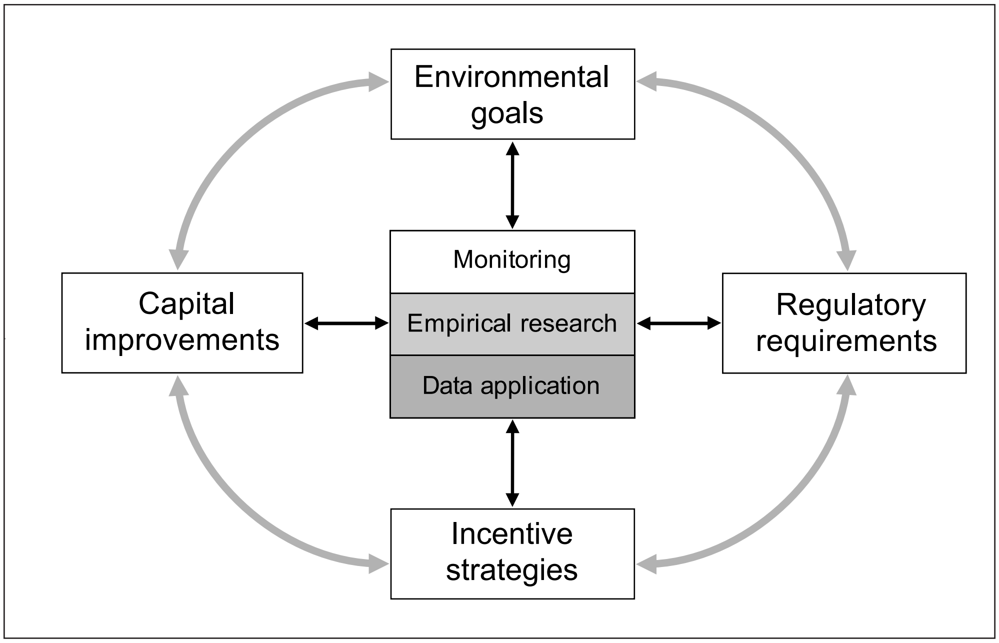

Figure 2.1—Illustration of the dynamic interface between an integrated science program (tri-shaded box) and the three types of implementation programs used to achieve and sustain the environmental thresholds or goals for the Lake Tahoe basin. The arrows indicate the pathways of information transfer and communication.

- **Status and trend monitoring**—The monitoring of the status and trends of resources, habitats, and their agents of change. This is the principal form of data gathering that informs management about overall environmental and resource conditions relative to established environmental objectives and thresholds. Typically, this type of monitoring serves to track the condition of indicators that have been selected to represent a set of conditions pertinent to environmental objectives.

Each of these types of monitoring is necessary to provide information of relevance to the management and conservation of habitats and resources in the Lake Tahoe basin (fig. 2.2). Integrated and coordinated monitoring programs are recommended to provide to agency managers and decisionmakers information about how implementation programs are affecting conditions in the Lake Tahoe basin. A multifaceted approach involves a dedicated and sustained effort to collect and analyze monitoring data on environmental and resource conditions at multiple spatial scales (project, watershed, and basin), in order to assess the effects of implementation programs, and progress toward achieving and sustaining environmental thresholds. Monitoring programs are best established in a coordinated and integrated framework so that information gains are maximized, while monitoring costs are minimized.

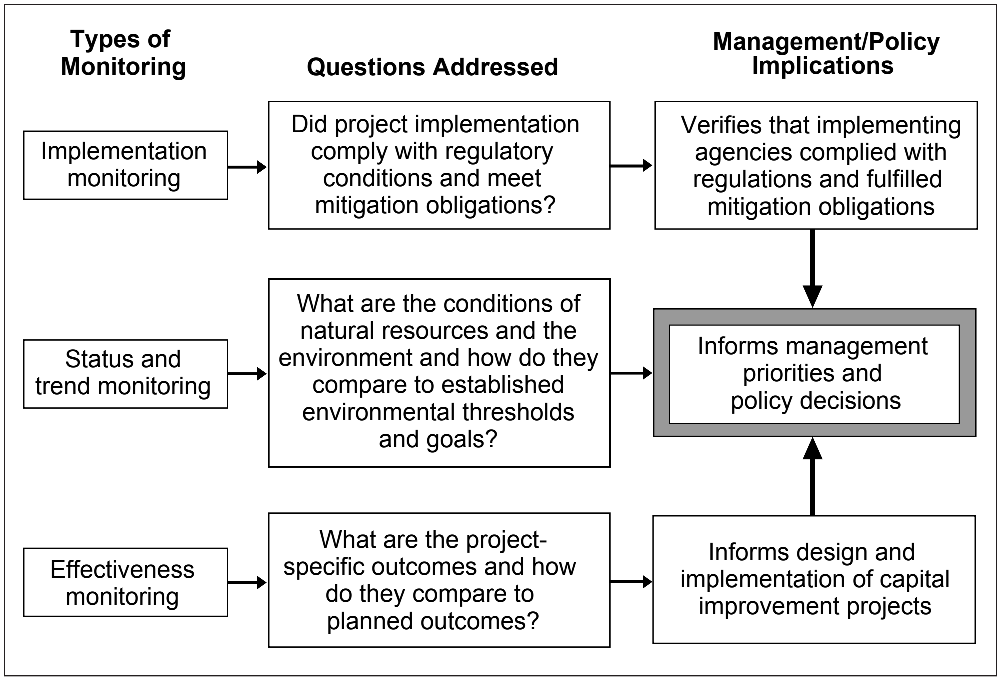

Figure 2.2—A conceptual diagram showing the relationships among various types of monitoring and the ways in which those types of monitoring can provide information to managers and policymakers. The questions also indicate how various types of monitoring provide information at the project, program, or, in the case of thresholds, basinwide scales.

Monitoring Priorities

Several monitoring needs were identified in discussions between scientists and managers during the course of developing this science plan. What emerged from those discussions is not a comprehensive list of the monitoring needs for the Lake Tahoe basin; rather, the list represents priority monitoring information needs within the next 5 years. A full array of important monitoring questions still awaits articulation by managers, ideally in collaboration with scientists. The allocation of resources to address monitoring information needs is outside the scope of the science plan, but will be essential to program success.

- **Meteorology and climate change.** Long-term, spatially relevant meteorological data on air temperature; wind speed and direction; humidity; timing; amount, and type of precipitation; annual hydrograph; snowpack; and snowmelt are recommended to support environmental studies in all issue areas. The technology to capture these kinds of data has advanced, which allows them to be collected more efficiently at more locations than in the past. These data are fundamental to informing questions about air quality, soil conservation, water quality, ecology, biodiversity, and climate change.

- **Air quality.** Improving Tahoe basin air quality monitoring is recommended by developing a comprehensive monitoring plan that addresses the criteria pollutants covered under the National Ambient Air Quality Standards (NAAQS) and those that impact human and ecosystem health (including water clarity) in an appropriate spatial and temporal framework. It is recommended that data collection use new technologies, including remote sensing and biomarkers. Once a plan is prepared, sampling locations can be chosen and appropriate air quality sensors can be deployed. Air quality and meteorological sensors would benefit from co-location to maximize efficiencies and information gain.
- **Water quality.** Initiate long-term status and trend monitoring of watershed hydrology and pollutant loads entering Lake Tahoe to (1) inform Lake Tahoe Total Maximum Daily Load (TMDL) land use and lake clarity models, and other water quality-related management models; (2) evaluate progress in meeting TMDL allocation requirements and other regulatory obligations; and (3) evaluate snowpack and snowmelt trends as they pertain to lake clarity. The Lake Tahoe Interagency Monitoring Program (LTIMP) partially meets these monitoring needs, but this program has eroded over the last decade owing to funding restrictions. The LTIMP does not include some key pollutant sources (i.e., urban stormwater and road runoff), and it does not include some key water quality constituents that directly affect lake clarity (i.e., particle number and particle size distribution). A regional stormwater quality/ best management practice (BMP) retrofit monitoring program is needed to assess the effects and effectiveness of capital investment projects at the project, watershed, and basin scales.
- **Soil conservation.** Develop and implement consistent and effective monitoring protocols for key soil properties and conditions. Monitoring protocols that are current, process-specific, and uniform across agencies and contractors would maximize effectiveness. Such a monitoring program is vital to informing the performance effectiveness of projects affecting soil properties and conditions throughout the Tahoe basin.
- **Ecology and biodiversity.** Develop a forest fuels reduction monitoring program to assess quantitatively the effects and effectiveness of fuels reduction projects at project, watershed, and basin scales. Establish a long-term, basin-wide status and trend monitoring program for terrestrial and aquatic biotic communities. It is recommended that biodiversity monitoring focus on the

composition of biotic communities and the distribution, frequency of occurrence, and abundance of native and nonnative species using direct measures and indicators to inform environmental thresholds and desired conditions. Monitoring data can provide a foundation for assessing the effects of climate change on terrestrial and aquatic biota of the Lake Tahoe basin. Status and trends monitoring are recommended for select focal species identified in regulations and basin management plans. Integration of focal species monitoring is recommended with biodiversity monitoring to the degree efficiencies can be gained, to provide reliable estimates of the population parameters targeted in those regulations and plans.

- **Social sciences.** Regular and systematic surveys are recommended to document the use of existing recreation resources and to help inform priorities for future facilities. It is recommended that those surveys be based on common methods so that data can be aggregated among sites to obtain regional and basinwide estimates of use.
    - Develop and implement the infrastructure to collect basic social and economic data throughout the Lake Tahoe basin. Common sampling methods are necessary to ensure that data can be aggregated and analyzed to assess socioeconomic conditions within the various municipalities, within geographic regions, and throughout the basin.
    - Infrastructure is recommended to support the centralized collection, inventory, and distribution of transportation data at regional and basinwide levels.
    - Establishment of a spatially and temporally appropriate monitoring program is recommended to allow for assessing noise conditions relative to established threshold indicators.

Research

Research can be defined as a structured process of inquiry that aspires to discover, interpret, and revise our knowledge of facts. Research aims to produce an ever-greater knowledge of events, behaviors, processes, theories, and laws. Research may include laboratory or field experiments, or the development of models.

Research is one of the fundamental ways in which science contributes to reducing uncertainties. Research and monitoring operate most effectively together. Monitoring, particularly status and trends monitoring, generates the knowledge necessary to pose new hypotheses about key cause-and-effect relationships, and the role of underlying processes in shaping ecosystems and their processes. Research is the means by which new hypotheses are tested in order to elucidate and confirm the relationships and interactions that determine the environmental conditions we observe and experience.

Research to support adaptive management often plays a relatively limited role in informing management decisions and policy choices, because obtaining new information is generally considered subordinate to demonstrating that policy choices and management actions have generated immediate results—such as on-the-ground projects, land preservation, or new regulations restricting a former activity—and that those results fulfill management objectives.

The single highest priority for research is to establish a stable funding stream to (1) ensure that the level of scientific understanding of the Lake Tahoe basin continues to develop, (2) create the research tools and techniques necessary to best inform policy choices and management strategies, and (3) support timely and effective science delivery in terms of research findings and management implications.

Over the past several decades, much of the available research funding has been allocated to address the factors and processes that specifically affect Lake Tahoe water quality, particularly lake clarity. Although great strides have been made in knowledge related to lake water quality, a similar level of progress in understanding other ecosystem elements, such as forest health, biodiversity, air quality, or socio-economic dynamics has not occurred. Although it is known that terrestrial, aquatic, and atmospheric habitats are interconnected, and that all are influenced by human activities, the direction and intensities of interactions and effects are in many cases uncertain. We recommend balancing the distribution of new research funds across multiple theme areas so that we simultaneously increase our knowledge base across a diversity of issue areas. Research needs specific to each of the five theme areas are presented in chapters 3 through 7.

Data Application

Data application includes the activities of analysis, reporting, management, and assessment in order to accomplish the following objectives: (1) manage data and information in ways that ensure their quality and availability; (2) complete analyses that convert data into information that can directly guide management; and (3) share that information with others, such that the information promotes knowledge. From a management standpoint, data application to real world problems may be the most important element of an integrated science program, because it is this activity that provides research and monitoring results in forms that managers can apply directly to management actions, decisions, and policy choices. To meet the growing data and information needs of resource management agencies and the public, it is important that data are translated into information and information is converted to knowledge as efficiently as possible to maximize its potential benefits. Ideally, a data management system works within existing institutional arrangements and policy requirements to meet agency communication and coordination needs, and allows for an integration of data and information sharing among a wide variety of entities inside and outside the Lake Tahoe basin.

Data Application Priorities

A dedicated source of funds and resources is recommended for data management, analysis, and reporting to ensure that this element of an integrated science program is accomplished and maintained. The identification of responsible entities and allocation of sufficient resources to fulfill this function is essential to achieving success and minimizing costs by eliminating redundant efforts among institutions. In the course of developing this science plan, a number of high-priority investments in data applications were identified for completion over the next 5 years.

- **Accomplishments report.** Completed annually, an accomplishments report from the science community would synthesize the results of research and other science projects completed during the previous year; this report would then be combined with updated running totals of administrative outcomes (e.g., dollars spent, number of projects completed) and program outcomes (e.g., acres restored, volume of stormwater treated) from the management agencies. The accomplishments report would summarize scientific findings and relate the importance of those findings to ongoing and future management activities and policies. This report also could identify research needs that have emerged as a result of monitoring results, new environmental conditions, or changes in policy or regulation. Information in the accomplishments report would help agencies and scientists track projects completed or in progress, and develop or adjust near-term priorities for capital projects, research, monitoring, and analysis. Information in the report also could provide a snapshot of project outcomes.
- **Central monitoring database.** The value provided by a centralized information depository is manifold; however, a primary goal is to promote the management of both research and monitoring data in a manner that ensures their quality and accessibility. It is recommended that infrastructure should be developed and maintained so that basic data and summary information is stored, integrated, and accessible to a diversity of users. The Tahoe Integrated Information Management System (TIIMS) has begun efforts to address the needs associated with this activity.

- **Environmental management knowledge base.** An environmental management knowledge base that documents our current understanding of conditions, interactions, threats, and desired outcomes can inform science and management priorities and activities. Integrated information systems can meet the array of information needs across institutions and disciplines in an efficient and transparent manner. Knowledge bases with their incumbent conceptual models provide valuable tools for integrated information storage and retrieval. A knowledge base of environmental quality for Lake Tahoe that serves both management and research would:
  - Provide a transparent basis for evaluating desired conditions.
  - Enhance the ability to communicate ideas and outcomes among stakeholders regarding management options at site and landscape scales.
  - Facilitate rapid access by decisionmakers to needed information.
  - Help prioritize information gaps to be filled and illustrate the basis of priorities.
  - Compare outcomes associated with various management options to help determine priority objectives for specific locations and how to balance objectives across landscapes.
  - Serve as a tool to interpret changes in desired conditions over time based on monitoring data.
- **State-of-the-Lake-Tahoe-basin report.** It is recommended that a state-of-the-basin report be completed every fifth year. This report could include a comprehensive synthesis of the research and monitoring that has been completed over the previous 5 years. Results could be framed in terms of an environmental report card for the Lake Tahoe basin, and would evaluate conditions relative to environmental goals and thresholds. This information could be used to evaluate and (if necessary) modify management strategies and implementation programs (i.e., inform the adaptive management process). This report also could alert high-level officials to emerging issues that may require new or alternative policies. The state-of-the-basin report would include at least the following subject areas:
  - Lake Tahoe
  - Basin watershed condition
  - Basin airshed condition
  - Living resources condition
  - Human environment

Adaptive Management

An integrated science program is best applied to land and resource management efforts using structured adaptive approaches, which are referred to as adaptive management. Adaptive management has been dubbed, "learning by doing," but that label understates the technical and institutional challenges in implementing the process and sustaining it over time. The essential elements of adaptive management include the clear articulation of management goals and objectives; the development of conceptual models that describe how managers believe the ecosystem works; the identification of alternative management responses; and an implementation strategy that describes management actions, tools, and expected outcomes. Successful application of adaptive management relies on various information inputs (e.g., scientific, legal, or economic) into each element along with processes that allow adjustments and adaptation. The aim is to develop policies and management strategies that are responsive to the best available knowledge and increase the chances of management success.

A variety of processes and techniques have been advanced to guide those who wish to transfer available scientific information to policymakers and resource managers under adaptive management. In the Lake Tahoe basin, agency leaders have agreed to work together to develop and operate an adaptive management framework as a means to (1) integrate management actions across targeted resources, including air quality, water quality, lake clarity, soils and vegetation, and wildlife and fisheries; (2) coordinate monitoring, research, and ecological and hydrological modeling efforts; (3) define responsibilities among those contributing to adaptive management for data analysis, interpretation of study results, and the reporting of new information; and (4) identify protocols to facilitate collaborative decisionmaking in resource management and environmental restoration and in the updating of management strategies (TRPA et al. 2007).

An operational science program for the Lake Tahoe basin should contribute pertinent and timely information to help guide management actions by informing data collection in monitoring and assessment efforts, and by building a foundation of reliable scientific information from directed research about the basin's ecosystems (fig. 2.1). Interactions among science, management, and policy are typically complex and iterative. For example, agency-defined environmental thresholds that at least in part have been informed by scientific information guide many of the actions of the Tahoe basin's capital improvement program, while at the same time regulations informed by the same and different information are intended to prevent further degradation of conditions relative to those thresholds (fig. 2.1). Management strategies and policy choices rely on iterative interactions among environmental goals and implementation programs. An integrated science program is most effective if it operates to provide information at the intersections among these programs and the goals that guide them. An integrated science program can provide information that is useful in verifying cause-and-effect relationships, assessing program effects and environmental conditions, and influencing the selection of management strategies and policies that can ultimately translate into funding decisions and courses of action for program implementation.

An adaptive management framework can provide links between management needs, scientific activities, and management actions, thus ensuring that the best available knowledge systematically informs planning and management activities (Manley et al. 2000). Incorporating a science program into an adaptive management framework explicitly acknowledges that critical uncertainties confront those who develop policies and implement management strategies. A functional adaptive management system will integrate the commitments to reducing uncertainty through research, monitoring, and data applications with the commitments to implement restoration actions.

An adaptive management framework typically makes explicit the linkages between information acquisition, management decisions, and management action (fig. 2.3). In the purest form of adaptive management, uncertainties associated with management policies and strategies are treated as working hypotheses and

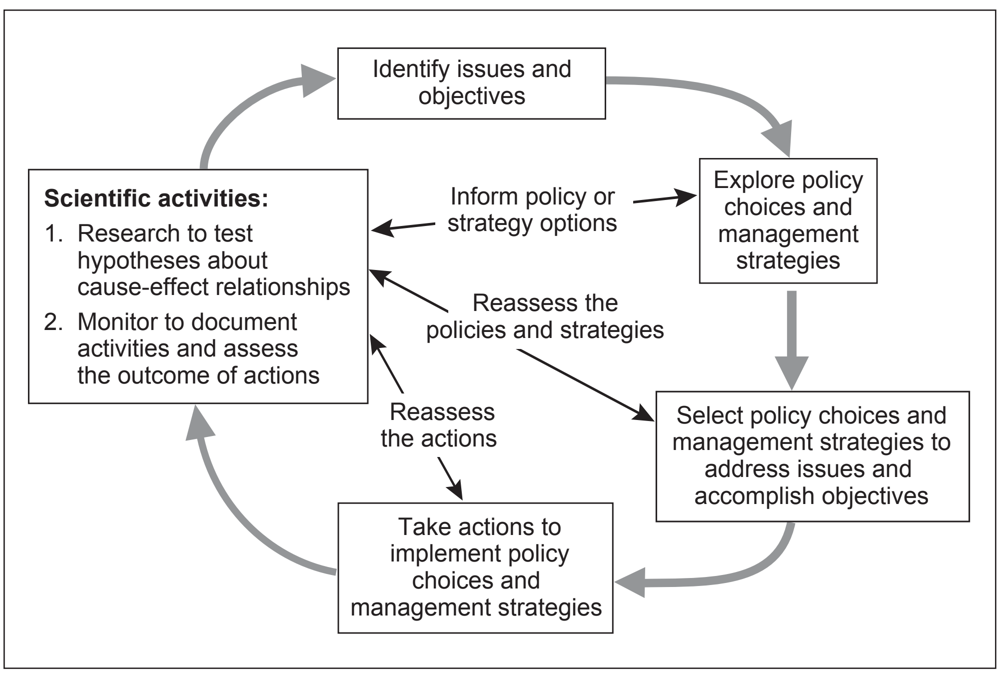

Figure 2.3—An adaptive management framework illustrating the major steps in a decisionmaking process, and the various linkages by which scientific information can inform each step in the process.

are not permanent features (Lee 1993). Working hypotheses are tested through research and monitoring, with the outcomes of these data-gathering efforts (i.e., experiments) providing opportunities to acquire new knowledge that can inform subsequent policy and management decisions (Hollings 1978; Lee 1993, 1999). Both research and monitoring are essential elements in this form of adaptive management, framing policy choices as working hypotheses, and testing those hypotheses.

In an appraisal of adaptive management, Lee (1999) found that "adaptive management has been more influential, so far, as an idea than as a practical means of gaining insight into the behavior of ecosystems utilized and inhabited by humans." As a result, adaptive management is frequently applied as a partial overlay to existing, frequently imbalanced infrastructure for problem identification, policy choices, and management actions. In such situations, opportunities to obtain new information are opportunistic endeavors that do not detract from the central objective of achieving management results. Accordingly, monitoring is viewed as the "science" needed to document the effects and effectiveness of management strategies. In either application of adaptive management, the role of science is to provide objective information that can tell us about the outcomes and consequences of actions or choices and that can help to improve future decisions.

Science Plan Conceptual Models

Conceptual models are an essential centerpiece of adaptive management and its integration of monitoring, research, and data applications into more effective, efficient, and accountable management actions. Their function is to communicate a shared understanding about the key elements, linkages, and stressors associated with ecosystems among those who are responsible for and contribute to their management. In essence, they document our hypotheses about how ecosystems function and thereby inform management planning, the development of assessment and monitoring programs, and the design of research efforts. Conceptual models that have been vetted through scientists, managers, and stakeholders can serve as the basis for numerical models that attempt to describe the consequences of alternative management actions. Without conceptual models, there can be no reliable adaptive management.

Conceptual models describe in graphical or narrative form the ecological system subject to management, allowing inference about how that system "works." A model of riparian forest function in the Lake Tahoe basin, for example, would describe the relationships between the vegetation and the animals that depend on it, the hydrological and other physical processes that affect those relationships, and the roles of human activities in disturbing and sustaining the system. Such models help to clarify the verbal descriptions of what we have observed in nature, and force us to think about ecosystem elements and interactions that we might otherwise ignore. In the formulation of a conceptual model, the combinations of parameters that drive ecological systems often become apparent, which in turn provides planners a more complete context to understand how various management strategies or regulations might affect system function and the condition of natural resources. Attributes of particular importance to ecosystem function and sustainability are strong candidates for management attention and assessment using monitoring. Conceptual models help us to assure that our current and future management actions target the correct ecosystem features and attributes, and increase the likelihood that our actions will produce the desired management outcomes. Acceptance of a common suite of conceptual models by agency and stakeholder representatives signals agreement regarding critical aspects of ecosystem well-being for which they share management responsibility.

A conceptual model should clearly identify key system elements and key physical and biological processes. The model should articulate how the system is impacted by stressors (i.e., disturbances and perturbations) from both natural and human-generated sources and how management can intervene to reverse undesirable conditions or trends. That description can take one or more forms, including box and arrow diagrams, cartoons accompanied by narrative descriptions, simple linear pathway illustrations, or even straightforward text descriptions.

Conceptual models will always fall short of a full and accurate portrayal of ecosystem elements and processes—highly detailed renditions would be counter to the primary objective of serving as a communication device among stakeholders. Their very imperfection is part of their utility, in that they make our understanding of how natural systems work available for review and discussion; thus, they help to identify areas of uncertainty and direct efforts to the information necessary to make better management decisions. Once agreement is reached among stakeholders on workable conceptual models, they can begin to serve as a framework for decision-support systems that can help managers evaluate the relative risks and opportunities associated with various management options. If adaptive management is effective, conceptual models will improve in their accuracy and effectiveness as we learn more over time.

We developed conceptual models for the Lake Tahoe basin Science Plan that had multiple objectives. They are intended to provide a roadmap to the key research needs identified in the theme areas considered in this science plan, orient the reader to the focal elements within each theme, and identify the interactions and linkages among these elements and the subthemes. Perhaps more importantly, they serve as a starting point for discussion and further development in collaboration with managers and other stakeholders in the Lake Tahoe basin. Here we provide an overview model of the primary elements of the research strategies and their linkages (fig. 2.4). The primary biophysical and sociocultural elements of each theme—the subthemes—are shown in association with their respective themes. The themes and subthemes are arrayed around a circle to indicate that they are all part of a single-basin ecosystem and thus affect one another to various degrees. Primary interactions between subthemes and across themes are indicated by arrows that span the circle. Interactions between subthemes within a theme are not shown—they are numerous and are addressed in the theme-specific models within each chapter.

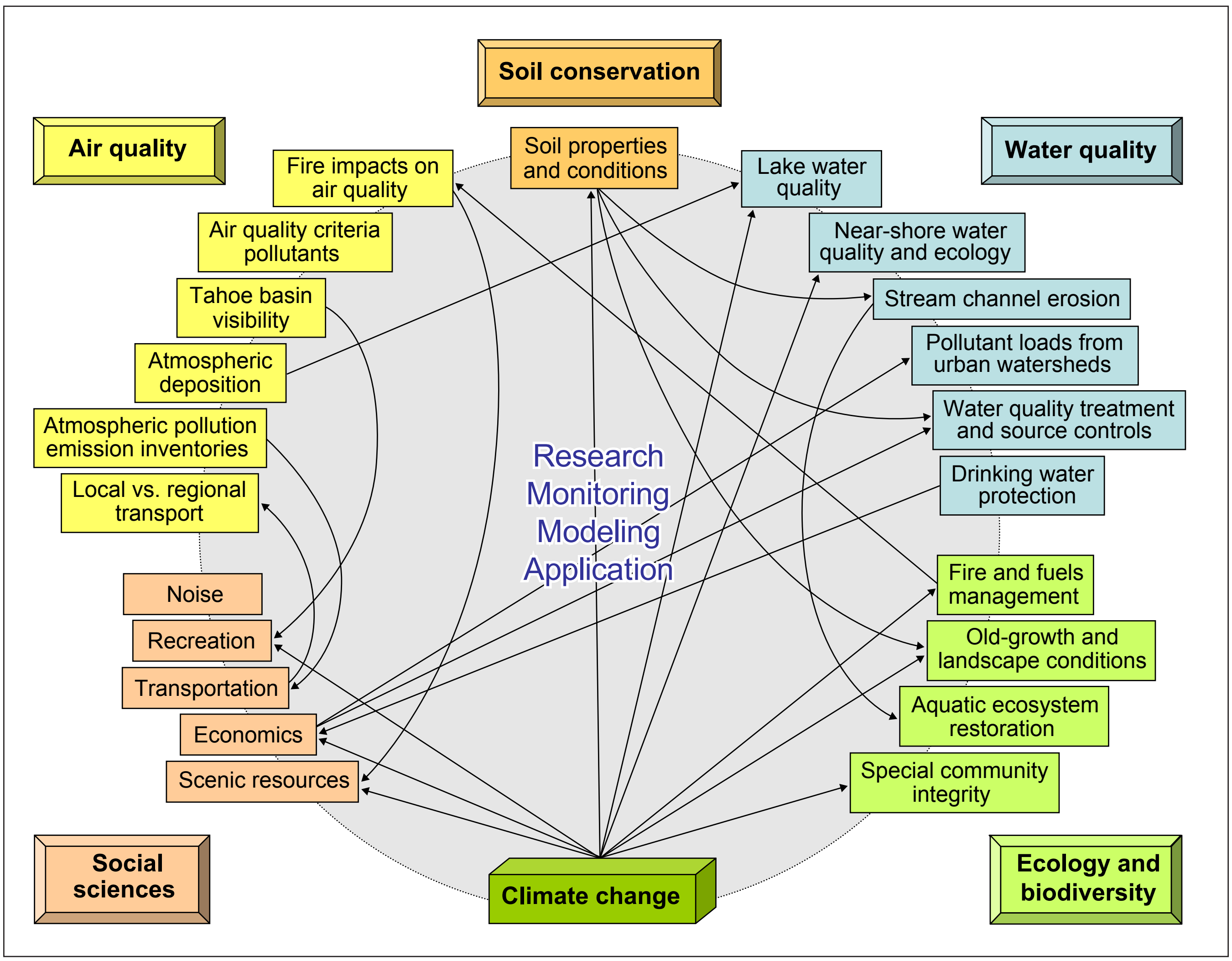

Figure 2.4—Overview conceptual model of the integrated science plan for the Lake Tahoe basin. The model includes the five theme areas covered in this science plan and the subthemes within them for which knowledge gaps and research needs are discussed as part of each research strategy. Climate change is included as an example of an environmental stressor, and its linkages to various ecosystem components are indicated.

Although the subthemes arrayed around the circle are unique to each theme, the themes share many features. Most environmental stressors affect multiple biophysical and sociocultural elements in various ways. Climate change, for example, has the potential of affecting every theme area and every aspect of well-being in the basin. Thus, climate change is shown as a stand-alone element and the subthemes that it is likely to affect first and most directly are indicated via arrows. Certainly, many other stressors, such as air pollution, urban development, and invasive species, affect multiple themes and subthemes. These stressors are discussed within each theme, but the development of stressor-based conceptual models would be a valuable future investment. Science-based activities in support of adaptive management are noted in the center of the circle—research, monitoring, modeling, and data application—indicating that they span subthemes and themes, and in fact are most effective when designed to do so.

More detailed theme-specific conceptual models appear in each theme chapter. They display the subthemes (focal points of the research strategy), the components of each subtheme, and what factors (drivers) affect them (fig. 2.5). The theme-specific conceptual models identify the linkages between drivers and components. The conceptual models identify the linkages or elements that are priority areas for research, and for which specific research needs are specified in the strategy based on the combination of risk and uncertainty. The models also identify basic information needs where those needs can be a barrier to informing management, and they suggest useful monitoring indicators. Once a knowledge base is designed around the conceptual model, it can be used to assess conditions and derive information on relationships among its component parts. The relationships among any of the component parts of the knowledge base can be represented in the form of summary tables or figures akin to conceptual models. Using a knowledge base for this function alone can address a number of the commonly posed questions about ecosystem interactions from a management perspective. The real power of the knowledge base, however, is in evaluating ecosystem conditions, both across the entire planning area and by planning unit.

The "box and arrow" conceptual models developed for this science plan are a common format for portraying basic parts and interactions of a system of interest. In the Lake Tahoe basin, the large number and scope of issues of interest and the complexity of their interactions make conceptual models a valuable and necessary tool—a means by which essential information can be displayed and understood. With such a complex problem set, however, it is challenging, if not impossible, to render a conceptual model that is sufficiently detailed to be representative, yet simple enough to be informative. Managers and scientists alike benefit from

1. Theme areas Theme	Definition: Primary categories of biological, physical, and social conditions of interest to agencies and the public. Constituents: Interest areas are divided into their primary elements (i.e., air quality, water quality, soil conservation, ecology and biodiversity, and integrating the social sciences into research planning. Condition: Degree of consistency with desired condition statements on condition of elements.
2. Subthemes Subtheme	Definition: Categories within theme areas identifying the distinct subsets of interest. Constituents: Subthemes are substantive topics that are important to consider within each theme area. Condition: Degree of consistency with desired condition statements based on condition of individual constituents, or an aggregation of constituents, depending on the desired condition.
3. Components Component	Definition: Broad categories representing the substance of each subtheme. Constituents: Each component is represented by one or more indicators and affected by one or more drivers. Condition: Degree of consistency with desired conditions based on condition of indicators. Information on indicators—what they represent and how their values are derived—is contained within this tier.
4. Drivers 1° Driver 2° Driver	Definition: Drivers are agents of change, natural or human-caused, that affect the condition of improvements and indicator values. Primary drivers affect change directly, while secondary drivers affect primary drivers and often reflect the ultimate causal factors for environmental change. Constituents: Each component is directly affected by one or more primary drivers, which in turn are directly affected by one or more secondary drivers.

Figure 2.5—Elements and framework used to develop theme-specific conceptual models.

conceptual models, but models tend to fall short of the need to portray and analyze environmental interactions and complexities. It is likely that land and resource management agencies will be investing in knowledge base decision-support tools, and they will need conceptual models to serve as the roadmap for these knowledge bases. The theme-based conceptual models presented in this science plan are intended to contribute to this management need.

Ideally, conceptual models serve as the basis for working models that can be used in an interactive decision-support process. Hierarchical knowledge-base models can be an effective approach to dealing with decisionmaking in a complex biophysical, sociocultural, and regulatory environment. In such models, the detailed complex interactions, as they are understood and refined over time, can be accurately represented and their relative influence on outcomes tested and quantified. Knowledge bases are a logical extension of conceptual models, and their development and application to decisionmaking in the basin will become increasingly important as scientists and managers face the substantial uncertainties about how to maintain and restore ecosystem resilience and sustainability. They are a form of metadatabases that represent a formal logical representation of a network of relationships among elements of interest. The structure of a knowledge base for Lake Tahoe would need to be designed to meet a spectrum of information storage and retrieval needs. It would need to contain information on broad categories of environmental quality and basic measures of their condition to meet the communication needs of managers and decisionmakers across institutions. It would also house the more detailed information associated with how the values of the measures are derived, and the uncertainties and risks associated with those values to provide a definitive link between information acquisition and application.

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Go to Part 2 (Chapters 3 and 4)

Chapter 3: Air Quality[1]

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Introduction

Air quality in the Lake Tahoe basin is known to affect lake water quality, forest health, and human health. The Lake Tahoe Watershed Assessment provided an initial summary of the status of our scientific knowledge regarding the factors leading to the observed decline in water quality (Reuter and Miller 2000) and steps that can be taken to restore the Lake Tahoe basin ecosystem (Murphy and Knopp 2000). Among the factors contributing to the decline in water quality are nitrogen (N), phosphorous (P), and sediment flow into Lake Tahoe. Cliff and Cahill (2000) reported that atmospheric deposition accounts for approximately 55 percent of the N and 15 percent of the P load into the lake. No estimate of atmospheric particulate input was presented. These estimates are highly uncertain. Although there has been extensive water sampling in the basin, there has been minimal air sampling. Thus, despite atmospheric deposition possibly being a major source of N input, a significant source of P input, and a potentially important source of particle deposition and sediment loading, we lack knowledge regarding the sources of these nutrients, the contribution from in-basin vs. out-of-basin pollutant sources, the spatial and temporal distribution of pollutant deposition, and the factors contributing to the observed deposition.

In addition to the issue of declining water clarity, there also are concerns regarding the impact of atmospheric pollutants on human and forest health and aesthetics. For example, the ozone (O_3) levels in the Lake Tahoe basin exceed

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current and proposed air quality standards that are designed to protect human health and welfare. In addition, elevated O_3 leads to a decline in forest health that can increase the threat of fire owing to dead and dying trees. In terms of particulate matter (PM), $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5µm or fine particulate matter) not only impacts in-basin visibility, but also is a concern because of its link to human health impacts.

To address the continuing concerns about air pollution impacts and develop a sound scientific approach for mitigating these impacts, this chapter updates the work of Cliff and Cahill (2000) and builds upon the Lake Tahoe Atmospheric Deposition Study (CARB 2006) by delineating remaining knowledge gaps and defining the research needs and strategies to close these gaps. To support this approach, a number of Tahoe-specific subthemes related to air quality were identified, including:

- Tahoe basin meteorology
- Atmospheric deposition of N, P, and particles
- Local vs. regional transport of air pollutants
- Tahoe basin air quality: the criteria pollutants
- Air pollution emission inventories
- Atmospheric modeling of the Lake Tahoe basin
- Impacts of fire on air quality

Climate change is likely to impact air quality through changes in emissions, activity, atmospheric transformations, and meteorology; however, at this time, these impacts are highly uncertain and have not been included in this summary.

In this chapter, we summarize our current state of knowledge on the selected subthemes and present the research needs and strategies that are recommended to improve our understanding of the impact of air quality on human health, water quality, and ecosystem health. We note up front that the lack of long-term comprehensive air quality monitoring data substantially affects our ability to fully develop an understanding of the atmospheric processes leading to pollutant impacts. Addressing this shortcoming would necessitate a long-term commitment to routine monitoring coupled with data interpretation to address the identified air quality knowledge gaps outlined in this chapter.

Conceptual Model

There are a number of coupled processes leading to air and water quality impacts caused by air pollution in the Lake Tahoe basin. Initially, we have emissions from both human activities and natural processes. For example, motor vehicle use results in the direct emission of carbon monoxide (CO), oxides of nitrogen (NO_x), hydrocarbons (HC, also referred to as volatile organic compounds, VOCs), and PM. Biogenic sources (i.e., trees) are a major contributor to VOC emissions. Following emission of pollutants into the air, meteorological factors influence pollutant concentrations through transport, dilution, temperature/relative humidity, and precipitation. Simultaneously, chemical transformations take place in the atmosphere, leading to the formation of harmful species such as O_3.

One issue of concern is the deposition of N, P, and sediment (related to PM) into the lake, which contributes to a decline in water clarity. As pollutants are dispersed and react in the atmosphere, they can also deposit on surfaces through either wet or dry deposition pathways. Both of these are important in the basin; although, given the sporadic nature of rain and snow, it is likely the dry deposition pathway dominates.

In addition to the water clarity issue, air pollutants can negatively impact both human and ecosystem health. One way to assess potential impacts is to monitor ambient pollutant levels and compare the results with ambient air quality standards that are designed to protect human health and welfare. Currently, the only basin pollutant in violation of the standards is O_3. Based on the determination of negative impacts (i.e., violation of the air quality standard, impact on water clarity, declining visibility, etc.), management agencies can develop policies to reduce pollutant levels. In general, these involve the reduction of emissions.

To aid management agencies in their efforts to improve air quality and mitigate negative environmental impacts, we can make use of a conceptual model (fig. 3.1). The four major components contributing come from mobile, area, stationary, and biogenic sources. Each of these has a number of 1° (primary) and 2° (secondary) drivers. For example, land use and transportation systems and policies (2° drivers) affect the number and activity of on- and off-road vehicles and business operations (1° drivers), which control mobile source emissions. Similarly, fire risk and suppression (2° driver) influences naturally occurring fires and plant and animal outputs (1° drivers) that contribute to biogenic emissions. It is important to note there are overarching drivers that cannot be controlled: chemical and physical transformations and meteorology and climate.

As described above, emissions from the four components lead to air quality and environmental impacts. These impacts can be identified and assessed using various indicators. Potential indicators in the Lake Tahoe basin are vehicle miles traveled and activity, measurements of long- and short-range visibility, air quality standards, concentrations of nonregulated pollutants, and measures of human and ecosystem health.

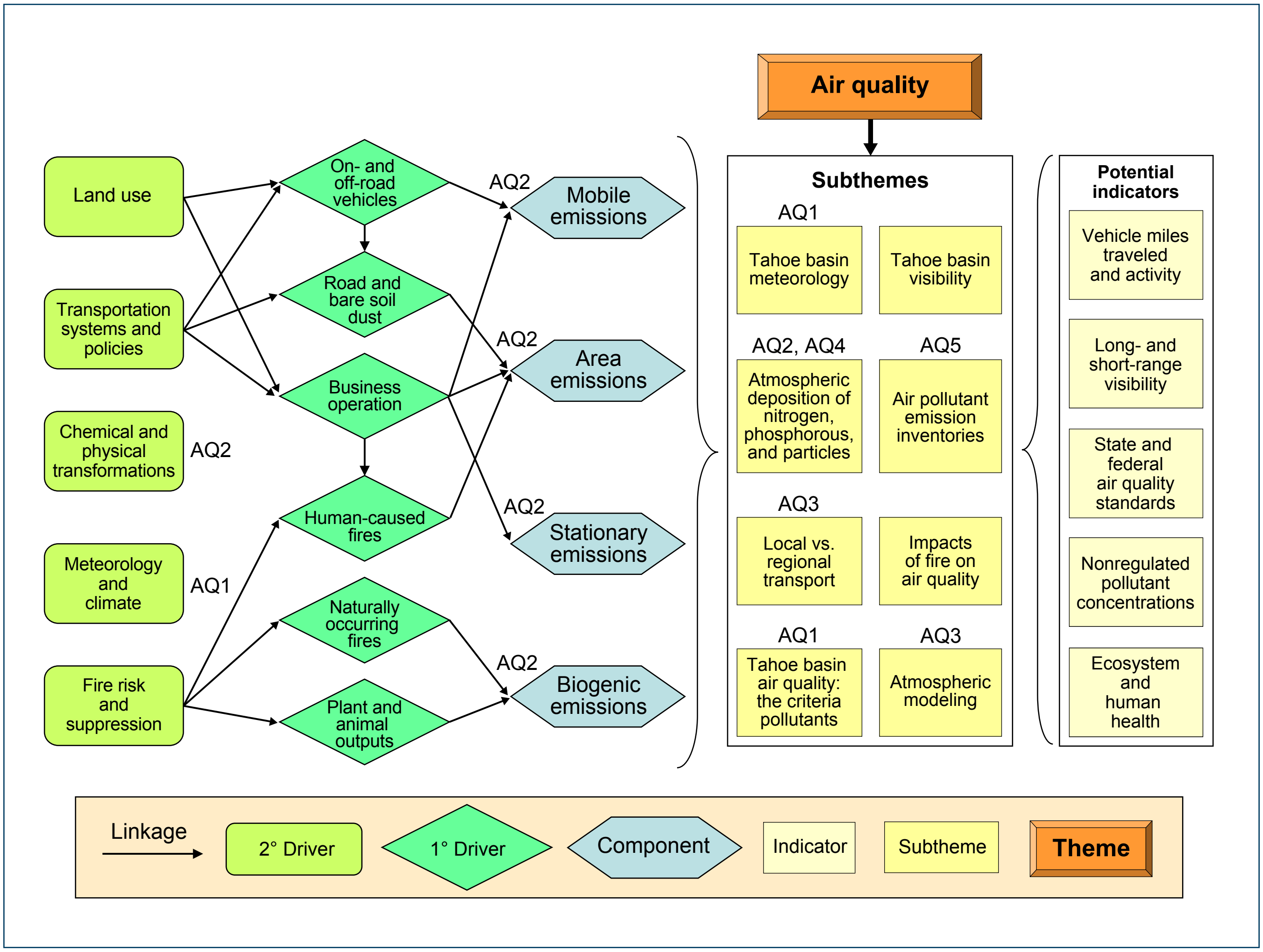

Figure 3.1—Conceptual model for Lake Tahoe basin air quality (AQ) subthemes. Identified are the primary sources of emissions in the Lake Tahoe basin airshed, the natural and human-caused drivers that affect these emissions, and arrows indicating the linkages among drivers and emission sources. These drivers and emission sources affect each of the air quality subthemes. Near-term air quality research priorities are indicated by symbols AQ1–AQ5 and correspond to the descriptions presented later in this chapter.

In this chapter, we've identified eight subthemes related to the various drivers and components outlined in the conceptual model that affect air quality issues in the Lake Tahoe basin. The sections that follow present the state of our knowledge regarding these subthemes and discuss measures that can be implemented to improve our understanding of the processes affecting air quality. By making use of the relationships among the various drivers, components, and indicators presented in this conceptual model, basin managers can develop effective strategies to improve air quality in the basin.

Tahoe Basin Meteorology

To understand the complex relationships among air quality, lake clarity, forest health, visibility, and human health in the Lake Tahoe basin, it is necessary to understand meteorology in and around the basin. Overall, our current understanding is limited and additional monitoring, research, and modeling efforts are needed.

The unique physical attributes of the basin play an extremely important role in defining the basin's atmospheric processes. There are generally two types of regimes that have the largest impact on atmospheric processes in the basin: thermal inversions and atmospheric transport.

Thermal inversions—

Because Lake Tahoe is located at a high elevation and surrounded by mountains on all sides, an atmospheric regime is created that, in the absence of strong synoptic weather systems, develops very strong, shallow inversions at all times of the year. Further, the rapid cooling at night generates downslope winds, which move from the ridgetops down and across populated areas and over the lake itself. Pollutants emitted by human and natural activities, along with those "carried in" with the downslope winds, will often become "trapped" at the surface (both land and lake surfaces) by thermal inversions, thereby creating areas of concentrated pollutant levels and increasing the chance for air pollutants to deposit on the lake and the surrounding watershed.

Atmospheric transport—

The location of Lake Tahoe directly to the east of the Sierra Nevada Mountain crest creates the second most common meteorological regime: atmospheric transport of air pollutants from the Sacramento Valley/Bay area into the Lake Tahoe basin by mountain upslope winds. This pattern develops when the western slopes of the Sierra Nevada are heated, causing the air to rise in a chimney effect and move upslope and over the Sierra crest into the Tahoe basin. The strength of this pattern depends on the amount of heating, thus is strongest in summer, beginning in April and essentially ceasing in late October (Cahill et al. 1997). This upslope transport pattern is strengthened and made even more frequent by the alignment of the Sierra Nevada range across the prevailing westerlies common at this latitude, which combine with the terrain winds to force air up and over the Sierra Nevada mountains from upwind sources in the Sacramento Valley (Cliff and Cahill 2000). So, although this process is often discussed in terms of the out-of-basin air quality impacts from pollutants generated in the Sacramento Valley and Bay area, the atmospheric transport regime can also include pollutant contributions from large-scale global atmospheric transport. For example, the atmospheric transport of dust from Asia has been detected in numerous areas across California's west coast and in the Tahoe basin (CARB 2003).

Another important meteorological regime, mediated by topography and low pressure systems, results in a summertime pattern that circulates moisture in from the east, often forming thunderstorms along the Sierra crest. In addition, strong high-pressure patterns north and northwest of Lake Tahoe can bring strong dry winds across the basin at almost any time of the year. Each of these meteorological regimes has a potential for concentrating anthropogenic pollutants within the Tahoe basin (Cliff and Cahill 2000).

Seasonal differences—

Seasonal differences in meteorology play a large role in air pollutant processes as well. In the summer months, nightly inversions are common, thereby contributing to higher pollutant concentrations in trapped areas. Additionally, summertime weather conditions such as higher temperatures and fewer storms create conditions favoring higher emission rates and concentrations of certain pollutants, such as O_3. More specifically, warmer temperatures can increase emission rates of pollutants from motorized equipment and biogenic sources. Further, secondary effects also can result in increased vehicle emissions owing to an increase in the number of vehicles within the basin because of the increase in popular summertime activities and the greater use of second homes. Another important meteorological regime generally associated with the summer months includes the atmospheric transport of pollutants from areas outside of the basin (see details under "Atmospheric transport" above).

Winter conditions in the basin are represented by cool temperatures and clear skies with periodic storms bringing precipitation in the form of rain and snow. These winter storms generally support strong vertical mixing in the atmosphere and the dilution of local and upwind pollutants while bringing in air from the very clean North Pacific sector (which accounts for the relatively low concentration of anthropogenic pollutants in the basin's snowfall [Cliff and Cahill 2000]). Unlike the nightly occurrences in the summer months, inversions in the winter months may last into the daytime hours. As with summer night conditions, there are certain pollutants for which emissions are higher during the colder months, such as CO from motor vehicle exhaust. The increased emission rates coupled with thermal inversions can create localized areas of unhealthy pollutant concentrations.

There are many weather stations of variable size and type, which have been operated by both private and public parties in the basin. These stations range from simple temperature and wind speed and direction monitors used by private citizens or companies, including ski resorts, and marinas, to those operated by government agencies and researchers who require quality-assured information to meet regulatory requirements and research needs. Unfortunately, the existing quality-assured weather stations are not yet extensive enough to answer the meteorological questions that remain. Further, simple ambient temperature and wind speed and direction measurements cannot account for the conditions that occur from ground level to thousands of meters above—a space that encompasses a very complex variety of atmospheric processes.

The most recent attempts to gather meteorological data at three locations in the basin occurred as part of the Lake Tahoe Atmospheric Deposition Study (LTADS), led by the California Air Resources Board (CARB 2006) in cooperation with other basin agencies. Unfortunately, this effort only continued for 1 year. This lack of consistent long-term meteorological measurements (and by extension, air quality monitoring) has hampered efforts to develop a better understanding of the factors influencing atmospheric processes in the basin.

One other issue not fully understood is the impact of climate change on Tahoe basin meteorology. Although it is likely this will lead to warmer temperatures in the basin, it is unclear how this will affect other variables such as relative humidity, wind patterns, and precipitation. All of these potential changes can greatly influence pollutant emissions and atmospheric processes leading to the deposition of N, P, and sediment to the lake.

Knowledge Gaps

Given the limited amount of high-quality meteorological data, there are substantial gaps in our understanding of the impact of meteorology on air quality. This has led to substantial knowledge gaps in the following areas:

- Spatial coverage of data collection is scarce, limiting our knowledge of microenvironments and our ability to accurately determine deposition in the basin.
- Only a limited number of meteorological variables are measured, making it difficult to employ detailed atmospheric models to assess atmospheric processes.
- There have been few upper air column measurements for use in evaluating chemical transformation and deposition pathways and validating atmospheric models.
- Advanced atmospheric models for use in evaluating management strategies have not been implemented for the Lake Tahoe basin, owing to the lack of adequate meteorological data.

Research Needs

- An appropriate air quality model needs to be developed that can utilize a full suite of meteorological data to better assess air pollutant trends, estimate impacts, and support the development of regulations that will assist in meeting air quality and other environmental goals. This model needs to be linked with an appropriate emissions inventory and relevant deposition data.
- Although existing meteorological information has provided researchers with a general understanding of typical meteorological regimes in the basin, far more monitoring locations and instruments are recommended to address the basin's air quality and lake clarity planning needs. Ideally this would include both ground-based and upper air column measurements.
- The seasonal impact of meteorology on pollutant levels with an emphasis on emissions from prescribed fires and wildfires should be evaluated using existing data.
- Seasonal overflights with light aircraft could be done to measure the concentrations of a number of air pollutants in the Tahoe basin and the meteorological conditions prevalent during these measurements. This will aid in the determination of meteorological conditions related to both deposition and in-basin vs. out-of-basin transport.
- Perform gradient flux or eddy correlation studies to determine pollutant deposition dynamics.

Atmospheric Deposition of Nitrogen, Phosphorus, and Particles

The atmospheric deposition of N, P, and particles to Lake Tahoe can be a substantial source of the pollutants contributing to declining lake water clarity (see section 4.5 in the "Water Quality" chapter of this science plan). Using on-lake deposition buckets, Jassby et al. (1994), Reuter et al. (2003), and Hackley et al. (2004, 2005) demonstrated that atmospheric inputs of N and P are a significant source of the nutrients supporting algal growth. Recent studies of water clarity implicate insoluble particles, largely soil derived, as important contributors to declining lake clarity (Coker 2000, Losada-Perez 2002, Swift et al. 2006). Preliminary estimates suggest that on the order of 15 percent of the fine, soil-derived particles enters directly into Lake Tahoe via atmospheric deposition (LRWQCB and NDEP 2008).

Deposition theory and validation have been summarized by Seinfeld and Pandis (1997). The dry deposition rate is codified by a net deposition velocity, which is, in turn, a sum of settling velocity for large particles and diffusion for small particles,

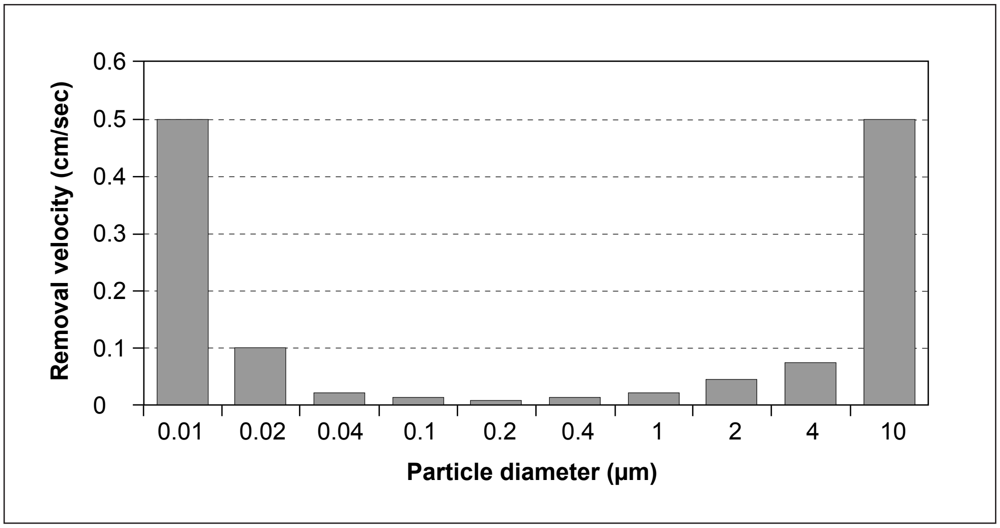

Figure 3.2—Plot of deposition velocities for particles. Above 0.3 µm, gravitational settling dominates, whereas below 0.2 µm, diffusion to surfaces dominates.

with the minimum total deposition velocity and thus the slowest removal rate occurring for particles in the range of 0.04 to 2.0 µm diameter (fig. 3.2).

This simple concept must be greatly modified in practice, when effects of boundary layer resistance and other factors are considered. Complex models have been developed to make these calculations, but direct in situ validation continues to be quite variable. No such model has been developed for Lake Tahoe, although the U.S. Forest Service (USFS) supported the development of a statistical model, the Lake Tahoe Airshed Model, in 2000 (Cliff and Cahill 2000).

In the 1980s, those working to understand the water quality trends in Lake Tahoe took a renewed interest in airborne nutrients (especially P and N) critical to algal growth. Studies of deposition elsewhere in the country (e.g., the Great Lakes) gave added impetus to this idea, as did the Nation's interest in acid rain and deposition of nitric and sulfuric acids. Airborne substances undoubtedly play a role in Lake Tahoe's water quality dynamics, but what role, exactly, was unclear at that time. In 1981 and 1982, the staff and consultants working on the Tahoe Regional Planning Agency's (TRPA's) threshold standards attempted to estimate the loading rate, in kilograms per hectare per year, of nitric acid that one might expect to see in the Sierra Nevada. Based on the responses received from scientific experts, TRPA estimated annual dissolved inorganic nitrogen load to the surface of Lake Tahoe on the same order of magnitude as the loads coming from surface streams and groundwater inputs. This conclusion—even without monitoring data to confirm it—influenced the development of TRPA's threshold standards and subsequent regional plan. It caused TRPA to look beyond erosion and runoff control as methods to control eutrophication.

In 1999, researchers from the University of California Davis and the Desert Research Institute worked with TRPA to develop the *Lake Tahoe Air Quality Research Scoping Document* (Reuter et al. 2000). Following the publication of that document and in support of the Lake Tahoe total maximum daily load (TMDL) program, a series of recent studies have attempted to estimate atmospheric deposition of N, P, and soil-derived fine particles. This was intended to update earlier nutrient budget estimates and to include for the first time the fine, soil-derived particles. The principal contributors to this effort were the CARB (CARB 2006), the Desert Research Institute (Tarnay et al. 2000, 2005), the UC Davis Delta Group (Cliff and Cahill 2000), and the UC Davis Tahoe Environmental Research Center (Hackley et al. 2004, 2005; Reuter et al. 2003).

Results of these studies showed good agreement in estimated atmospheric deposition of N and P based on both modeling and direct-measurement approaches. Current estimates for loading directly to the lake surface from total N-deposition are about 200 metric tons per year (including inorganic and organic N), 6 to 8 metric tons per year for total P, and about 750 metric tons per year for soil-derived fine particles (<20 µm in diameter). Based on the revised atmospheric deposition estimates, the percentage contribution via atmospheric deposition directly to the lake surface relative to the other major sources is about 55 percent for total N, about 15 percent for total P, and about 15 percent for soil-derived fine particles. Recent studies shed light on the sources of P. Cahill (2005) found that most of the P mass was associated with local roadway soils and in particles > 10 µm diameter, and thus previously unmeasured. These data were put into Lake Tahoe Atmospheric Model (LTAM) and provided the deposition estimates reported by Gertler et al. (2006).

Knowledge Gaps

- Spatial information of on-lake dry and wet deposition measurements is scarce, and almost all measurements are limited to the northern one-third of the lake. The difference between nearshore and offshore deposition (in terms of amount, chemical species, and particle size distribution) is not well understood, yet critical to whole-lake deposition estimates.
- Information on spatial and temporal distribution of aerosol measurements by size and composition is scarce and rarely matches the deposition sites for validation.
- Routine measurements of gaseous (nitrogen oxides, ammonia, and nitric acid [NO_x, NH_3, and HNO_3, respectively] and organic nitrogen species are limited or nonexistent in the basin, leading to a large uncertainty in the N-deposition estimates.

- Air quality models have not been developed that adequately incorporate Lake Tahoe's complex meteorological conditions.
- The deposition of "black carbon" to the lake and its impact on water clarity have not been studied. Black carbon (also known as elemental carbon) is most evident as soot, and is formed through the incomplete combustion of fossil fuel, biofuel, and biomass.
- The distribution between the amount of N, P, and sediment deposited by wet and dry deposition pathways is uncertain.
- The greatest uncertainty in the deposition estimates is associated with soil-derived particle deposition to the lake surface (only 1 year of limited data exist). In addition, estimates of wet deposition of particles are based on measurements that are less direct than measurements of dry deposition of particles.
- The impact of N and P atmospheric deposition to the lake surface in the summer is not well understood. This is a time when biologically available N and P are low and watershed loading is at its annual minimum.
- Atmospheric loading onto the water surface could have a disproportionate effect on lake clarity within the 20- to 30-m Secchi depth; however, this has not been evaluated.
- Atmospheric deposition studies have not accounted for the contribution of pollutant fallout to the land surfaces surrounding Lake Tahoe that is subsequently delivered to Lake Tahoe via hydrologic processes.
- Existing data are not readily available.

Research Needs

- Conduct focused studies (gradient or eddy-correlation studies, along with measurements of key species) of the sources and pathways of particle deposition to better inform models and restoration efforts.
- Add deposition sites on the lake and in the middle and southern sections along the lake.
- Conduct deposition measurements along nearshore-offshore transects and data sets that allow averaging among seasons.
- Add gaseous monitoring capabilities to existing and future sites.
- Add size-segregated and chemically speciated aerosol measurements to quantify the relationship between deposition of particulate matter expressed in terms of weight and the particle chemical composition and size distribution most likely to affect lake clarity.

- Pursue development of a detailed air quality model that includes transport and deposition modules specific to Lake Tahoe conditions. Develop these models for use as water quality management tools.
- Determine the possible influence of "black carbon" deposition to the lake.
- Ascertain the relationship between pollutants entering via atmospheric deposition and the effects on lake clarity.
- Develop and sustain the infrastructure to combine data from all sources, archive results in easily accessible sources, and publish results.

Local Versus Regional Transport of Air Pollutants

Atmospheric pollutants deposited in the Lake Tahoe basin can come from both in-basin and out-of-basin sources (see "Conceptual Model" section and fig. 3.1 for details). In terms of hemispheric atmospheric circulations, California is within the latitude range of prevailing westerly winds. However, because of relatively weak synoptic forcing, wind patterns tend to be modified by differential heating between the land and ocean. Previous studies have described the typical summer flow pattern in California as the marine air that penetrates through the Carquinez Straight and bifurcates around the delta region into south and north branches (Frenzel 1962, Hays et al. 1984, Moore et al. 1987, Schultz et al. 1961, Zaremba and Carroll 1999). This primary pattern is superimposed by thermally driven daytime upslope and nighttime downslope flows, hence making pollutant transport possible from the more heavily polluted regions, such as the San Francisco Bay area and the Sacramento Valley, up into the Sierra Nevada mountains.

To quantify how much HNO_3 is transported from the Central Valley, Sacramento, and San Francisco Bay area to the Tahoe basin, Koracin et al. (2004) used advanced numerical atmospheric models (CALMET/CALPUFF, Scire et al. 2000 and MM5, Grell et al. 1995) to estimate the contributions from both in-basin and out-of-basin N sources. Simulations of in-basin emissions and out-of-basin emissions were performed separately to determine their relative contributions. The overall simulation results indicated that pollutant transport from the Sacramento Valley and the San Francisco Bay area to the Lake Tahoe basin occurs; however, as indicated in previous studies (Bytnerowicz et al. 2002, Carroll and Dixon 2002, Dillon et al. 2002), pollutant concentrations are significantly diluted on the west slopes of the Sierras at increasing elevations (fig. 3.3). In short, the results of the Koracin et al. (2004) work suggest that although daytime pollutant transport from upwind of the Lake Tahoe basin appears to be likely, the amount of HNO_3 transported into the basin is much less than that from in-basin sources. Note that estimates of the transport of additional N species (e.g., ammonia, ammonium, nitrate,

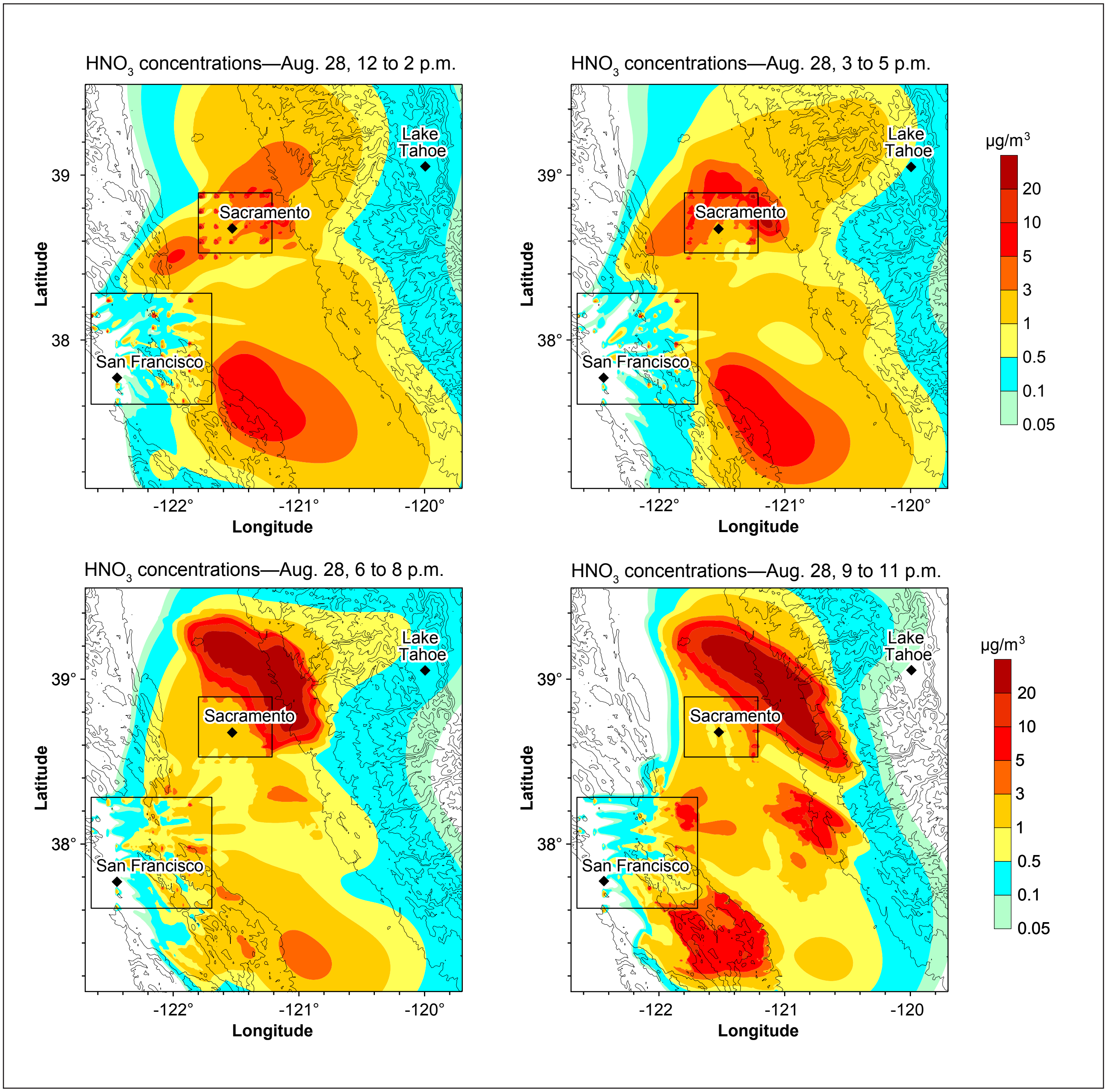

Figure 3.3—Nitric acid (HNO_3) ($\mu g/m^3$) plume evolution from the Central California Valley on August 28, 2000, beginning at noon (left panel) and continuing to 11 pm (right panel) from Gertler et al. (2006). Concentrations (filled contours overlaid with topography) are averaged over 3-hour intervals. The enclosed areas surrounding Sacramento and San Francisco designate the emission sources. Note the effects of daytime upslope flows (upper left panel) and nighttime downslope flows (lower right panel). Pollutant concentrations at elevated regions are low, implying minimal HNO_3 transport to the basin.

nitrogen dioxide, or nitric oxide [NH_3, NH_4, NO_3, NO_2, and NO, respectively]), and the contribution from wet deposition were not determined as part of this study.

One of the great difficulties in evaluating air pollution transport into the Tahoe basin is the lack of data on the upwind western slope of the Sierra Nevada. Bytnerowicz et al. (2004) addressed this problem by using inexpensive passive samplers deployed throughout the region. Using a set of O_3 and HNO_3 concentration measurements, a spatial model of pollutant concentrations was constructed (Frączek et al. 2003). Frączek et al. observed a clear pattern in O_3 and HNO_3 concentrations over the course of the smog season with the lowest levels occurring in the first half of July and the first half of October, and the highest levels occurring in the second half of August. Elevated O_3 and HNO_3 concentrations southeast of the Tahoe basin were observed in the second half of August through the second half of September. Seasonal averages for HNO_3 are shown in fig. 3.4.

For all pollutants, Bytnerowicz et al. (2004) found decreasing concentrations entering from the west into the Tahoe basin, indicating minimal transport to the lake. They postulated that the mountain range west of Lake Tahoe basin (i.e., Desolation Wilderness) creates a barrier that prevents polluted air masses from the West (Sacramento Valley and foothills of the Sierra Nevada) from entering the Lake Tahoe basin.

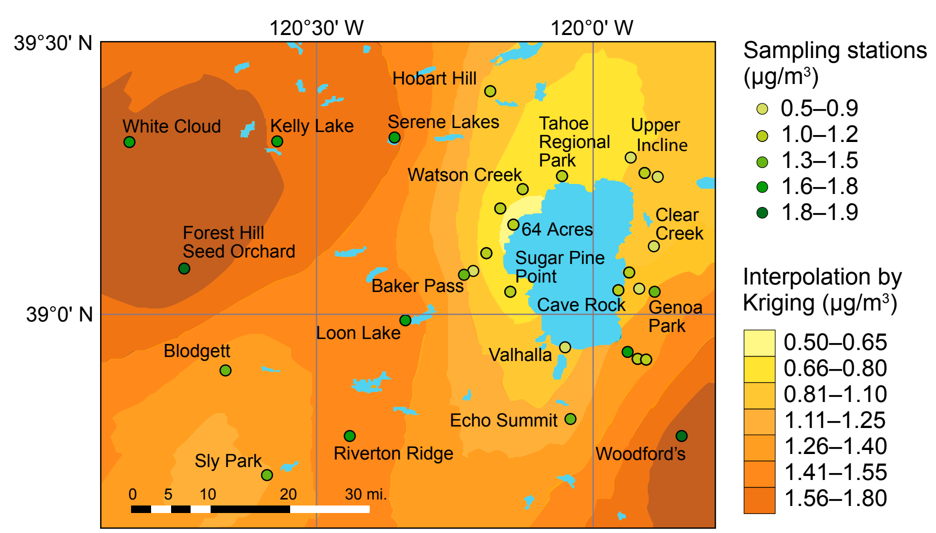

Figure 3.4—Distribution of ambient nitric acid (HNO_3) concentrations ($\mu g/m^3$) in the Lake Tahoe basin and its vicinity in the 2002 summer season from Gertler et al. (2006). Maximum levels (dark brown) are observed west of the lake and decrease with increasing elevation.

Cahill et al. (2004) used size-segregated chemically speciated measurements of chemical species to address the issue of in-basin versus out-of-basin sources of P. Measurements were performed in January 2002 and August 2002 using a particulate sampler developed at UC Davis (Cahill and Wakabayashi 1993) instead of using filter-based measurements. Samples were collected at the South Lake Tahoe site for 12 weeks in winter and 6 weeks in summer to allow analysis of synoptic weather patterns. They found that almost all the P observed occurs in the size fractions between 2.5 and 35 µm, consistent with the theory that resuspended road dust and soil is the major source. Previous studies in the area have used samplers with a 2.5-µm cut-point and thus would have missed the contribution from larger size fractions. This implies that most of the P comes from in-basin sources, as particles in this range tend to deposit rapidly.

Based on these findings, it appears that the majority of atmospheric species contributing to declining lake water clarity in Lake Tahoe come from in-basin sources. Using the emissions inventory estimates presented in the "Visibility in Lake Tahoe" section, the major in-basin sources of N, P, and fine particles are emissions from motor vehicles and areawide sources (e.g., paved and unpaved road dust and residential fuel combustion). In terms of the O_3-forming precursors, the most likely sources are motor vehicles and biogenic emissions.

Knowledge Gaps

- To date, studies have indicated most of the N, P, and sediment deposition come from in-basin sources; however, out-of-basin sources contribute to N, $PM_{2.5}$, and O_3 levels in the basin. Quantifying these out-of-basin contributions is recommended.
- The spatial and temporal resolution of airborne N, P, and particles is limited. Most measurements have been performed as part of intensive studies and do not cover all periods of the year or a range of meteorological conditions. In addition, many key species and parameters are not monitored (e.g., gaseous N species, P, or size-segregated aerosol chemistry).
- There are limited measurement sites both in the basin and leading up to the basin for use in assessing the sources of the pollutants.
- Direct measurements of plume transport to the basin and deposition have been limited or nonexistent.

Research Needs

- Perform air quality measurements of key species under a range of meteorological conditions. Include measurements for NO_x, NH_3, HNO_3, size-segregated aerosol mass, particle number and particle size distribution, and aerosol chemical composition. Consider the use of advanced monitoring techniques such as differential optical absorption spectroscopy, remote sensing, and the use of airborne platforms to obtain additional data on key atmospheric species.
- Add air quality monitoring stations in the basin, on the ridges leading into the basin, and on the west side of the Sierra Nevada Mountains to assess in-basin vs. out-of-basin sources throughout the year and under different meteorological conditions.
- Monitor plume transport using an aircraft platform to directly assess the pollutant contribution from out-of-basin sources and link these measurements to deposition.
- Develop a Tahoe-specific modeling system that includes appropriate emissions data to evaluate in-basin vs. out-of-basin sources of observed pollutants.
- Complete a meta-analysis of existing work on the conclusions for wet/dry and in-basin versus out-of-basin contributions. A fair amount of data and information exists, but no one has completed a comprehensive synthesis. Additional research questions would then come from this work.

Tahoe Basin Air Quality: The Criteria Pollutants

The Tahoe Regional Planning Agency Compact, amended in 1980, called for TRPA to adopt environmental threshold carrying capacities (“thresholds”) to protect the values of the Tahoe basin. The first set of comprehensive air quality thresholds were adopted by TRPA in August 1982; however, compliance with TRPA’s threshold standards as well as changing federal, state, and local air quality and visibility standards could require amendments to the thresholds. Currently, the TRPA is developing a new regional plan that may include new thresholds, indicators, standards, and regulations for air quality. Table 3.1 presents an overview of the attainment status and trend based on the recent analysis (TRPA 2005) of each criteria air pollutant where attainment of standards has been an issue. For reference, federal and California air quality standards for CO, O_3, respirable particulate matter (PM_{10}), and fine particulate matter ($PM_{2.5}$) are shown in table 3.2. Note that monitoring locations in the basin have been chosen to provide information related to air quality standards, rather than to obtain data for deposition assessment. A discussion of the issues associated with each of these pollutants is presented below.

Table 3.1—Air quality indicator attainment status[a]

Threshold criteria air pollutant	Attainment status 1991	1996	2001	2006	5-year trend
Carbon monoxide	Nonattainment	Attainment	Attainment	Nonattainment	Positive
Ozone	Nonattainment	Nonattainment	Nonattainment	Nonattainment	Unknown[b]
Particulate matter (PM_{10})	Nonattainment	Nonattainment	Attainment	Nonattainment	Unknown

[a] Results for 1991 to 2001 were obtained from Tahoe Regional Planning Agency (2005).
[b] More stringent ozone standards became effective in May 2006. This may result in additional ozone violations in the future.

Table 3.2—California and federal air quality standards

Air quality constituent	Averaging time	California standard	Federal primary standard
Carbon monoxide	8 hr	9 ppm	9 ppm
	1 hr	20 ppm	35 ppm
	8 hr (Tahoe)	6 ppm	N/A
Ozone	8 hr	70 ppb	75 ppb
	1 hr	90 ppb	None
Particles less than 10 µm in diameter	24 hr	50 $\mu g/m^3$	150 $\mu g/m^3$
	Annual arithmetic mean	20 $\mu g/m^3$	None
Particles less than 2.5 µm in diameter	24 hr	Same as federal	35 $\mu g/m^3$
	Annual mean	12 $\mu g/m^3$	15 $\mu g/m^3$

Note: The Nevada standards are the same as the federal standards.

Carbon monoxide—

Carbon monoxide is a tasteless, odorless, and colorless gas that is slightly lighter than air and is associated with substantial health risks especially at high altitudes. It affects humans by reducing the supply of oxygen to body tissues. The primary source of CO emissions is combustion of hydrocarbon fuels by motor vehicles; home heating devices such as fireplaces, stoves, and furnaces; and industrial processes. In the Tahoe basin, the primary source of CO emissions is from mobile sources such as motor vehicles and boats. For this reason, it is important to concentrate on transportation improvements within the basin as a control method for reducing CO levels. Owing to the substantial health risks posed by CO, the TRPA, California, Nevada, and the federal government have all adopted standards for this pollutant.

Carbon monoxide is considered a “hotspot” pollutant, meaning elevated levels are very localized. Thus, it is necessary to use data from multiple monitoring stations within the basin to report on this pollutant. Currently, CO is only measured at one location (South Lake Tahoe), which does not provide the necessary data to either evaluate ambient conditions or make recommendations for improvements.

Ozone—

Ozone is a secondary pollutant that is formed in the atmosphere by a photochemical process involving HC, NO_x, and sunlight. This pollutant poses a substantial health risk especially to the young and elderly in the form of lung and other respiratory illnesses. Ozone also damages trees and plants, particularly ponderosa pines (*Pinus ponderosa* Dougl. ex Laws.), Jeffrey pines (*Pinus jeffreyi* Grev. & Balf.), and quaking aspen (*Populus tremuloides* Michx.) (Davis and Gerhold 1976, Miller et al. 1996). Ozone precursors are produced from human activities such as the combustion of fossil fuel, chemical processing, fuel storage and handling, and solvent usage. As with CO, the primary source of O_3 precursor emissions in the basin is vehicle exhaust. Currently, O_3 is measured at two locations (South Lake Tahoe Airport and Incline Village). However, as is the case for CO, this does not provide the necessary data to either evaluate ambient conditions or make recommendations for improvements.

Particulate matter—

Particulate matter (PM) pollution consists of very small liquid and solid particles in the air. Two fractions of PM are generally measured: (1) PM_{10} (particulate matter with aerodynamic diameter less than 10 µm) and (2) $PM_{2.5}$. The primary sources of PM_{10} in the basin include motor vehicles, sand, salt and road dust, smoke from both natural and human-set fires, and fugitive dust from construction and the landscape. PM_{10} can increase the number and severity of asthma attacks, cause or aggravate bronchitis and other lung diseases, and reduce the body's ability to fight infections. These effects are particularly harmful to children, exercising adults, and the elderly. PM_{10} was only measured at the South Lake Tahoe site from 2001 to 2005 by CARB. As with the other pollutants, PM_{10} measurements are inadequate.

Fine particulate matter, $PM_{2.5}$, also is of concern. These particles have been linked to increases in human mortality and morbidity (Pope and Dockery 2006). $PM_{2.5}$ is primarily generated from combustion processes and can contain significant amounts of carcinogens. California and the federal government have adopted standards and have increased efforts to study and control this pollutant. $PM_{2.5}$ is measured at the two IMPROVE sites located at South Lake Tahoe and D.L. Bliss State Park. Coverage throughout the basin is inadequate to evaluate ambient conditions or offer recommendations for improvement.

There are a number of issues associated with the implementation of new air pollution standards and thresholds. These include:

- Not all agencies are in agreement that a single standard for the criteria pollutants is appropriate basinwide. Currently, there are different pollution standards and measurement protocols for each state, local, and federal agency with jurisdiction in the basin. This leads to confusion and the expenditure of substantial amounts of resources to keep track of each of the multiple standards.

- A permanent criteria pollutant monitoring program is lacking. The basin's air quality monitoring program has suffered greatly in the last few years owing to reductions, relocation, or removal of various monitoring stations and the lack of adequate resources to implement this program.
- An improved modeling system for criteria pollutants is needed. Although commonly available in other air basins, critical tools necessary to relate pollutant emissions to ambient and local air quality are lacking for the Lake Tahoe air basin. Specifically, these include updated activity data for each emissions source and an emissions model. Without these tools, the ability to assess the effectiveness of past or future emission reduction strategies is substantially limited.
- There is a lack of information on ecosystem health effects of the criteria pollutants. Although numerous air quality standards have been established by the U.S. Environmental Protection Agency (U.S. EPA), California, Nevada, and TRPA, these standards were primarily implemented for human health concerns. Although it is understood that these standards provide some protection for the ecosystem, additional information is needed to ensure these standards adequately protect the ecosystem health of the basin.

Knowledge Gaps

- What is the mechanism to adopt uniform standards for the criteria pollutant in the basin?
- How many air quality monitoring sites are necessary and where they should be located to adequately monitor the basin for criteria pollutants and their sources and what species should be measured? What air quality monitoring is necessary to evaluate programmatic changes? Should monitoring capabilities be added to obtain deposition data?
- To improve and update the emissions inventory, what are the activity, population, and emission factors that control emissions from the various sources of criteria air pollutants in the basin?
- For the cases where standards are exceeded, what are the appropriate emission reduction strategies to use in the basin? What are the costs, effectiveness, and constraints of each strategy?

- To develop thresholds that protect ecosystem health in the basin, what are the appropriate ecosystem health standards for criteria pollutants that need to be considered?

Research Needs

- Conduct studies to determine the number, distribution, and sampling frequency and protocol of a monitoring network that is adequate to obtain information related to air quality standards or other pollutants of interest (e.g., polycyclic aromatic hydrocarbon (PAHs), size-segregated and chemically speciated PM, and HNO_3). As part of this study, consider alternative monitoring techniques such as remote sensing or biomarkers (i.e., lichens).
- Develop basin-specific activity rates, emissions inventory, and emission models necessary to evaluate the present and future conditions and programs in the basin. Develop emission estimates for transportation and other large-scale programs included in the various planning and programmatic documents produced by basin agencies.
- Complete studies to inform implementation of the programs aimed at reducing the criteria pollutants emission levels in the basin. It is recommended that these studies also could provide information on cost, effectiveness, implementation issues, and constraints.
- Complete studies to determine the appropriate standards for criteria pollutants that protect ecosystem health in the basin. Primary concerns would focus on water quality and the clarity of lakes, as well as vegetation and wildlife health.
- Implement studies to assess the impact of pollutant levels (e.g., $PM_{2.5}$ and PAHs) on the health of humans living at altitudes similar to that of the Lake Tahoe basin.

Visibility in Lake Tahoe Basin

Visibility is an indicator of air quality, and good visibility is a desired condition in and of itself. The original visibility thresholds for the Lake Tahoe basin were first developed by the TRPA in the early 1980s after analyzing data collected in a short-term (June 1981 to May 1982) visibility monitoring program (Pitchford and Allison 1984). Both regional (basinwide) and subregional thresholds were developed from this study. Regional visibility is defined as the overall prevailing visibility in the Lake Tahoe basin. The primary impact of regional visibility degradation is a general reduction in clarity, contrast, and color of vistas seen through the regional haze. Subregional visibility in the Lake Tahoe basin is characterized by a layer of perceptible haze that spreads over the urbanized areas, especially the south shore of the lake.

When the regional visibility thresholds were defined, it was thought that optical measurement techniques of the period (long-path horizon/sky contrast) would be unduly influenced by meteorological conditions, thus indicating below-standard conditions, when in fact the air in the basin was quite clean (low aerosol concentrations). Because the South Lake Tahoe aerosol consists of a large fraction of absorbing aerosols (e.g., aerosols composed of elemental carbon), it also was realized that basing the subregional standard on nephelometers that only measure the scattering coefficient, would significantly underestimate the true subregional visibility. As a result, an interesting hybrid was developed for both the regional and subregional thresholds. The standards were defined in terms of an optical property—visual range—but the results were calculated from high-quality speciated aerosol data. At the time these standards were developed, no guidelines existed for using the calculations. It was thought that proper algorithms would be developed as visibility research matured.

In 1989, TRPA instituted a visibility monitoring program to gather the data necessary to address its visual air quality standards. The program was fully operational and funded by 1991. Details of the program are discussed elsewhere (ARS 1989, 2000). The monitoring program consisted of two major, fully instrumented sites—Bliss State Park and South Lake Tahoe—and one additional site that has had some periodic measurements: Thunderbird Lodge. The TRPA operated the Bliss State Park site from 1990 to November 1999. In December 1999, the Bliss State Park site was added to the national IMPROVE monitoring network, with funding provided by the US EPA. Both sites were operated by Air Resource Specialists, Inc. In June 2004, TRPA permanently shut down the South Lake Tahoe site.

Results from detailed analyses of the limited 1981–82 measurements and monitoring data collected between 1989 and 1991, indicated that within the experimental uncertainty of the 1981–82 measurements, there was no statistically observable change in the visual air quality levels in the Lake Tahoe basin between 1981 and 1991. Thus, in 1999 after further monitoring, TRPA restated visibility standards in terms of the current monitoring and data analysis techniques and set the baseline period as 1991–93 (table 3.3).

Table 3.3—1999 Tahoe Regional Planning Agency visual air quality environment threshold carrying capacities, 1991–93 baseline

Area	Visibility threshold
Regional visibility (Bliss to Round Hill)	Achieve a visual range of 156 km (b_{ext} = 25.1 Mm^{-1}) at least 50 percent of the year as measured by particulate concentrations
	Achieve a visual range of 115 km (b_{ext} = 34.0 Mm^{-1}) at least 90 percent of the year as measured by particulate concentrations
Subregional visibility (South Lake Tahoe)	Achieve a visual range of 78 km (b_{ext} = 50.2 Mm^{-1}) at least 50 percent of the year as measured by particulate concentrations
	Achieve a visual range of 31 km (b_{ext} = 126.2 Mm^{-1}) at least 90 percent of the year as measured by particulate concentrations

Two additional TRPA standards were adopted in the early 1980s:

- Regional visibility: Reduce wood smoke emissions by 15 percent from the 1981 base values.
- Subregional visibility: Reduce wood smoke emissions by 15 percent and suspended soil particles by 30 percent from the 1981 base values.

These stated reduction goals in wood smoke emissions and soil particulate concentrations appear to have been added as qualitative guidelines even though they are stated as specific reduction percentages. There are no existing valid estimates of wood smoke emissions for 1981, thus deciding if a 15 percent reduction has occurred is impossible. The reference to "soil" in the subregional visibility standard is not well understood. There is no existing record of what "soil" means, i.e., PM_{10} mass, reconstructed $PM_{2.5}$ fine soil, or more probably coarse mass (the resultant PM_{10} to $PM_{2.5}$ gravimetric mass). Thus, these additional standards have not been addressed in any meaningful fashion. However, given the new-found importance of the effects fine soil particle deposition on lake water clarity, the TRPA standard to reduce suspended soil particles by 30 percent from 1981 base values takes on increased importance.

Figure 3.5 shows the TRPA visibility standard cumulative frequency plots for the baseline period 1991–93 and 2001–03. As can be seen, subregional visibility has improved dramatically since the 1991–93 baseline. Regional visibility has improved on the cleanest and average (50 percent frequency) days, but has not improved much on the haziest (90 percent frequency) days. The TRPA is recommending through the Pathway process to replace the 1991–03 baseline with the 2001–03 period (table 3.4). This is an attempt to prevent the loss of any visibility improvements that have occurred in the basin.

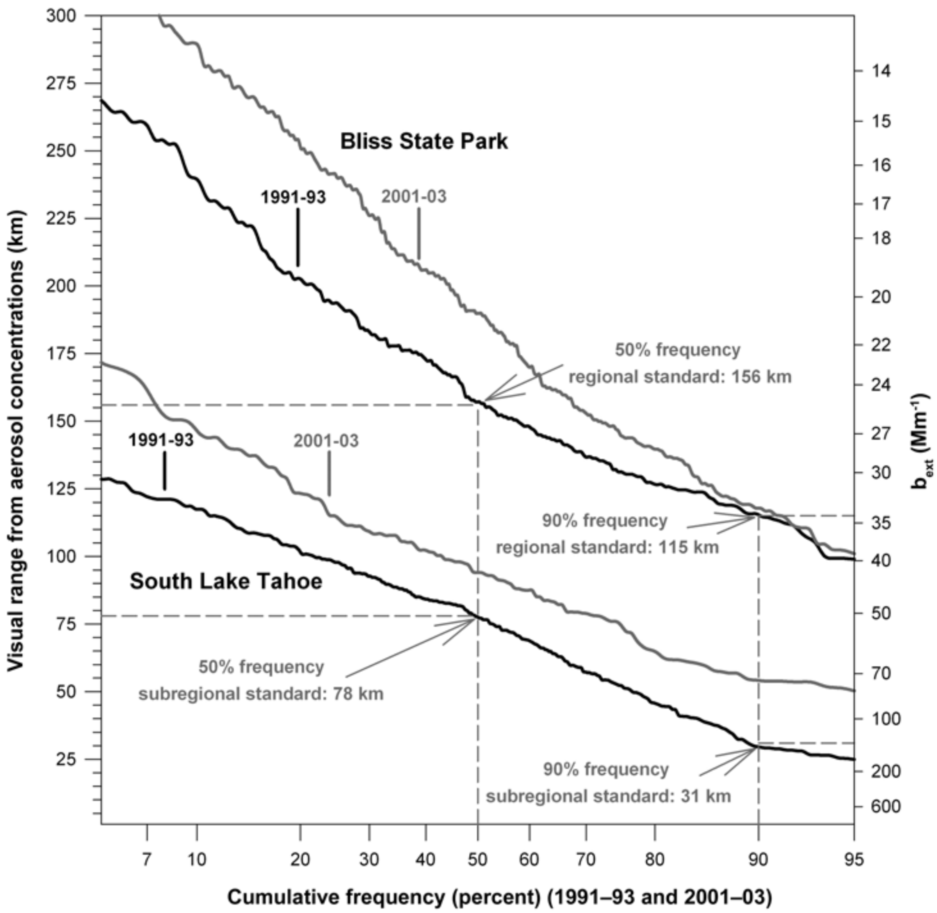

Figure 3.5—Tahoe Regional Planning Agency visibility standards: cumulative frequency plots of reconstructed extinction for 1991–93 (baseline year) and 2001–03 (from TRPA 2005).

Table 3.4—2006 proposed Tahoe Regional Planning Agency visual air quality environment threshold carrying capacities, 2001–03 baseline

Area	Visibility threshold
Regional visibility	Achieve a visual range of 188 km (b_{ext} = 20.8 Mm^{-1}) at least 50 percent of the year as measured by particulate concentrations
	Achieve a visual range of 116 km (b_{ext} = 33.7 Mm^{-1}) at least 90 percent of the year as measured by articulate concentrations
Subregional visibility	Achieve a visual range of 93 km (b_{ext} = 42.1 Mm^{-1}) at least 50 percent of the year as measured by particulate concentrations
	Achieve a visual range of 55 km (b_{ext} = 71.1 Mm^{-1}) at least 90 percent of the year as measured by particulate concentrations


Scott Hinton

Exhaust plume from a diesel truck located on a side road off of Highway 89, near Meyers, California.

Currently there are a number of concerns regarding visibility monitoring in the Lake Tahoe basin. The Bliss State Park site has been in continuous operation since 1990. Its operation and maintenance are currently funded by the US EPA as part of the IMPROVE monitoring network; however, funding and continued operation are uncertain. The South Lake Tahoe visual air quality monitoring station is now permanently shut down owing to loss of the property lease. This site was only 100 m west of the earlier South Lake Tahoe location; thus data from the site are deemed appropriate for use in the TRPA Subregional Visual Air Quality standard calculations. There was no available location near the two past monitoring sites that would allow direct continuation of the subregional speciated aerosol monitoring record. A new monitoring site has been installed in South Lake Tahoe. However, it is quite a distance from Highway 50 and the old monitoring sites. No overlapping time series exists, so comparisons among the sites are not possible.

Knowledge Gaps

- Visibility measurement locations are limited in the Lake Tahoe basin compromising the ability to accurately estimate regional and subregional visibility.
- Standards have been adopted requiring percentage reductions in emissions, but the link between changes in these sources and the effects on visibility are unclear.

Research Needs

- Expand the spatial distribution of the visibility monitoring network to include locations in addition to Bliss and South Lake Tahoe is recommended.
- Address the current lack of measurements related to the subregional standard.
- Quantify the contribution of wood smoke and other sources in the basin.

Air Pollutant Emission Inventories

Optimally, emission inventories (EIs) describe the magnitude, along with when and where various pollutants are emitted in a regional domain. Because emissions are generated from numerous intermittent sources (e.g., fireplaces, disturbed land, vehicles, and commercial businesses), assembling a comprehensive emission inventory would include the use of careful assumptions, which result in a product that will achieve the necessary objectives. Uses of EIs include:

- **Planning**—As populations and activities change within a region, it is useful to know how this will affect emissions and ultimately atmospheric concentrations.
- **Mitigation**—Knowing the sources and magnitudes of pollutants allows for the design of cost-effective control measures that will reduce atmospheric concentrations.
- **Simulation**—EIs are used as inputs to air pollution dispersion models to simulate the impacts of sources on atmospheric concentrations within the modeling domain.
- **Monitoring**—Tracking changes in emissions is useful for interpreting other long-term time series such as lake sediments and atmospheric concentration records. Correlations between emission records and these time series provide strong empirical evidence to relate sources to the observed levels of pollutants in the air and lake sediments.

Because ambient concentrations of aerosols within the Lake Tahoe basin are below the National Ambient Air Quality standards, the primary objective of a Tahoe-specific EI is to focus mitigating efforts to protect human health and improve lake water clarity.

A preliminary EI was assembled for Lake Tahoe as part of the CARB LTADS (Kuhns et al. 2004). In this study, local emission factors for road dust, vehicle exhaust, and residential wood combustion were measured in the basin. Wood-burning activity data were collected via a survey of local residents (Fitz and Lents 2003). Vehicle exhaust emissions were derived from an estimate of the number of gallons of gasoline and diesel sold in the basin. Road dust was estimated from Department of Transportation published data of vehicle miles traveled. These data were supplemented with CARB county-level emission inventories and extrapolated to the portions of the Nevada counties that fell within the Tahoe basin. Emissions from wild and prescribed fires were not included in the EI owing to a lack of information on the quantity of fuel burned throughout the year. Table 3.5 shows the estimates of a variety of air pollutants that culminated from that study.

Note that many of these sources are estimated with the goal of building a comprehensive California EI. As a result, some sources such as farming operations and unpaved road dust were estimated by scaling measurements collected in other counties to the Tahoe basin based on population or land area. These assumptions are unlikely to introduce a large error on the total statewide emissions; however, they are likely to be inappropriate for the specific needs of the Tahoe basin.

Courtesy of Tahoe Regional Planning Agency

Airborne dust created during bike trail sweeping near Tahoe Pines, California.

Table 3.5—Emission inventory results for the Tahoe basin[a]

Source	TOG	ROG	CO	NO_x	PM	PM_{10}	$PM_{2.5}$
	Megagrams per year						
Natural (nonanthropogenic) sources	0	0	30	0	5	5	5
On-road mobile sources[b]	1,019	935	2,489	148	7	7	4
Aircraft	112	99	998	73	34	30	30
Recreational boats	344	318	2,500	103	22	17	13
Off-road recreational vehicles	547	503	1,751	34	0	0	0
Off-road equipment	241	219	1,777	602	43	43	39
Fuel storage and handling	56	56					
Residential wood combustion and campfires[b]	570	251	6,400	187	726	680	653
Farming operations	392	30			60	26	4
Construction and demolition				366	176	39	
Paved road dust[b]				628	287	48	
Unpaved road dust				1,138	679	145	
Fugitive windblown dust				17	9	4	
Waste burning and disposal	202	90	1,162	30	133	129	120
Cooking	4	4			17	13	9
Solvent evaporation	422	387					
Stationary sources	413	254	43	82	9	4	4
Total	4,321	3,148	17,151	1,260	3,206	2,105	1,118

Definitions of emissions are as follows:

TOG = total organic gases, ROG = reactive organic grasses, CO = carbon monoxide, NO_x = nitrogen oxide, PM = particulate matter, PM_{10} = particles less than 10 micrometers in diameter, $PM_{2.5}$ = particles less than 2.5 micrometers in diameter.

[a] Emissions were estimated by scaling the California Air Resources Board Tahoe Air basin emissions with a multiplier based on land area, population, or vehicle kilometers traveled.

[b] Sources measured as part of the Lake Tahoe Atmospheric Deposition Study.

The Desert Research Institute recently completed a year-round monitoring program in the Lake Tahoe basin to measure the emissions of PM from roadways. The results of this study were integrated into a model to estimate emission factors based on the existence of emissions controls as well as meteorological and seasonal data for all road types in the Lake Tahoe basin. In addition, the study examined the effectiveness of emissions controls (i.e., sweeping, stormwater diversion systems, paved shoulders, and track-out prevention) for reducing particulate emissions (Kuhns et al. 2007).

A new project to improve these estimates and allocate them spatially within the basin has been approved for funding via the US EPA Region IX with funding from the Southern Nevada Public Lands Management Act. This study has recently been completed and will provide a detailed emissions inventory for the criteria pollutants and other key species (e.g., NH_3). Based on this inventory, the major contributors to ambient pollutants are as follows:

- CO: Mobile sources and residential fuel combustion. There is a strong seasonal dependence in the residential fuel combustion source.
- PM_{10}, $PM_{2.5}$, P, and phosphate (PO_4): Areawide sources, particularly residential fuel combustion and road dust resuspension. Emissions are significantly higher during the winter. Use of the road sediment data obtained with the DRI TRAKER (an instrumented vehicle developed to quantify silt loading on roads) significantly reduced the estimated resuspended road dust contribution when compared with the previous inventory.
- NO_x and NH_3: Mobile sources are the dominant contributor.
- VOCs: Mobile sources, biogenic sources, and areawide sources all contribute to VOC emission. There is a strong seasonal dependence in the biogenic and areawide source contributions

Knowledge Gaps

Linking air pollutant emissions to endpoints of interest (e.g., lake water clarity, or impacts to human or ecosystem health), creates some unique requirements for a Tahoe-specific EI. To develop cost-effective mitigating strategies that will improve water clarity, the following topics not generally included in EIs are recommended:

- The EI should account for the major species that are impacting the lake, specifically crustal particulates, N and P.
- Evaluation of the uncertainty and measurement of the size and composition of the particulates emitted from different sources.
- Accounting for emissions from events such as wildfires and prescribed burns, which can contribute to pollutant emissions.
- Addressing the lack of knowledge regarding the impact of wet deposition and scavenging by vegetation that may ultimately contribute to pollutant runoff into the lake.
- Knowing what N and organic species are emitted locally and what are transported into the basin in order to accurately simulate the fate and transport of N in the basin.

Research Needs

- It is recommended that emissions be geo-referenced to their specific sources (i.e., roads, erodible hillsides, beaches, residences, and fire sites). Additional work on the emissions inventory may be necessary to evaluate the contributions from out-of-basin sources.

- It is recommended that emissions for specific events (i.e., wild and prescribed fires) be estimated on a case-by-case basis, based on acreage and fuel mass burned. Numerous specific measurements are needed to develop confident regional or basinwide estimates.
- For smaller ubiquitous sources (i.e., residential wood combustion and vehicle exhaust), the development of seasonal profiles is recommended to accurately simulate how their magnitude changes over the course of a year.
- It is recommended that source samples from major sources be reanalyzed using techniques that can better resolve the concentrations of bioavailable N and P, and distinguish the number and size distribution of fine soil particles that affect lake clarity.
- Development of mobile source emission factor models for Tahoe-specific conditions (e.g., vehicle age and model year distribution, altitude, or grade) is recommended.
- Regular updates of activity estimates (e.g., vehicle miles traveled) are recommended.
- It is recommended that the inventory estimates be compared with water and air concentrations to make sure the results are consistent with what can be empirically observed. When inconsistencies are observed, additional research could be recommended to improve estimates and reduce uncertainty.
- Determine size-segregated PM emissions to better understand transport deposition processes.
- It is recommended that the inventory be used to assess health impacts and additional information related to this need be included.
- Apply receptor modeling techniques (e.g., chemical mass balance and positive matrix factorization) to validate the emissions inventory.

Atmospheric Modeling of the Lake Tahoe Basin

Currently, the only available model specific to the Lake Tahoe basin is the LTAM. The LTAM is a heuristic model that was designed more to merge existing data into a self-consistent framework than derive results from first principles, a so-called deterministic model. The model was developed to analyze the effects of prescribed fires and wildfires on air quality ($PM_{2.5}$ mass) and visibility, and would need some modifications and enhancements to handle deposition into Lake Tahoe for water clarity analysis.

The LTAM is a gridded model, dividing the Lake Tahoe air basin into 1,500, 2.59-km^2 domains. Each domain has a land use type (e.g., forest, lake, or urban), potential sources (e.g., transport from upwind, fire smoke, urban emissions, or roadway emissions), meteorological transport (mean 12-hr day, 12-hr night, summer, winter), and particle removal rates (e.g., deposition to trees, lake surface). Sources generate aerosol masses that are passed downwind from cell to cell with lateral dispersion and removal rates included, based upon lateral wind variability from the South Lake Tahoe data. Cliff and Cahill (2000) provided a full description of the model development.

One of the most difficult problems in developing a model at Lake Tahoe is that the data sources are widely dispersed in space and time. For example, there is excellent meteorology for 1½ years at Tahoe City in 1967, daytime values from the South Lake Tahoe airport, and local metrology at the ARB Sandy Way Bliss, and TRPA SOLA sites.

Figure 3.6 presents an example of the LTAM calculation for smoke from a 101 ha/day prescribed fire in the upper Ward Creek watershed. Nighttime downslope winds drive the smoke out over the lake, but note that relatively little smoke has penetrated to the southern end of the basin. The basic framework of LTAM was validated in 1999 via a 121-ha fire on Spooner Summit. The model output was compared to mass data from filter samples, with the results directly reflecting particle mass and indirectly reflecting visibility reduction. However, there are additional enhancements needed to meet the needs of water clarity. These enhancements are partially driven by improved water clarity models (Losada-Perez 2002, Schladow et al. 2004) that identify, in addition to the standard nitrate and phosphate inputs, airborne fine particles as an important factor in lake clarity. The most important enhancements involve incorporation of the new CalTrans data on soils, improved data on P from prior TRPA and LTAD studies, incorporation of the LTAD spatially and temporally dispersed data, and an enhanced particle deposition algorithm. These results can then be directly compared to the long-term record from the deposition buckets on and near the lake (Jassby et al. 1994).

Recently, an extensive study was conducted on both sides of Highway 50 in order to examine emissions of particulate matter (and P) from roadways (Cahill et al. 2006). These data were used to update the LTAM and enhance its ability to predict P concentrations in the basin. Figure 3.7 shows an example of the updated LTADS predictions for a fire event incorporating both fire and traffic impacts.

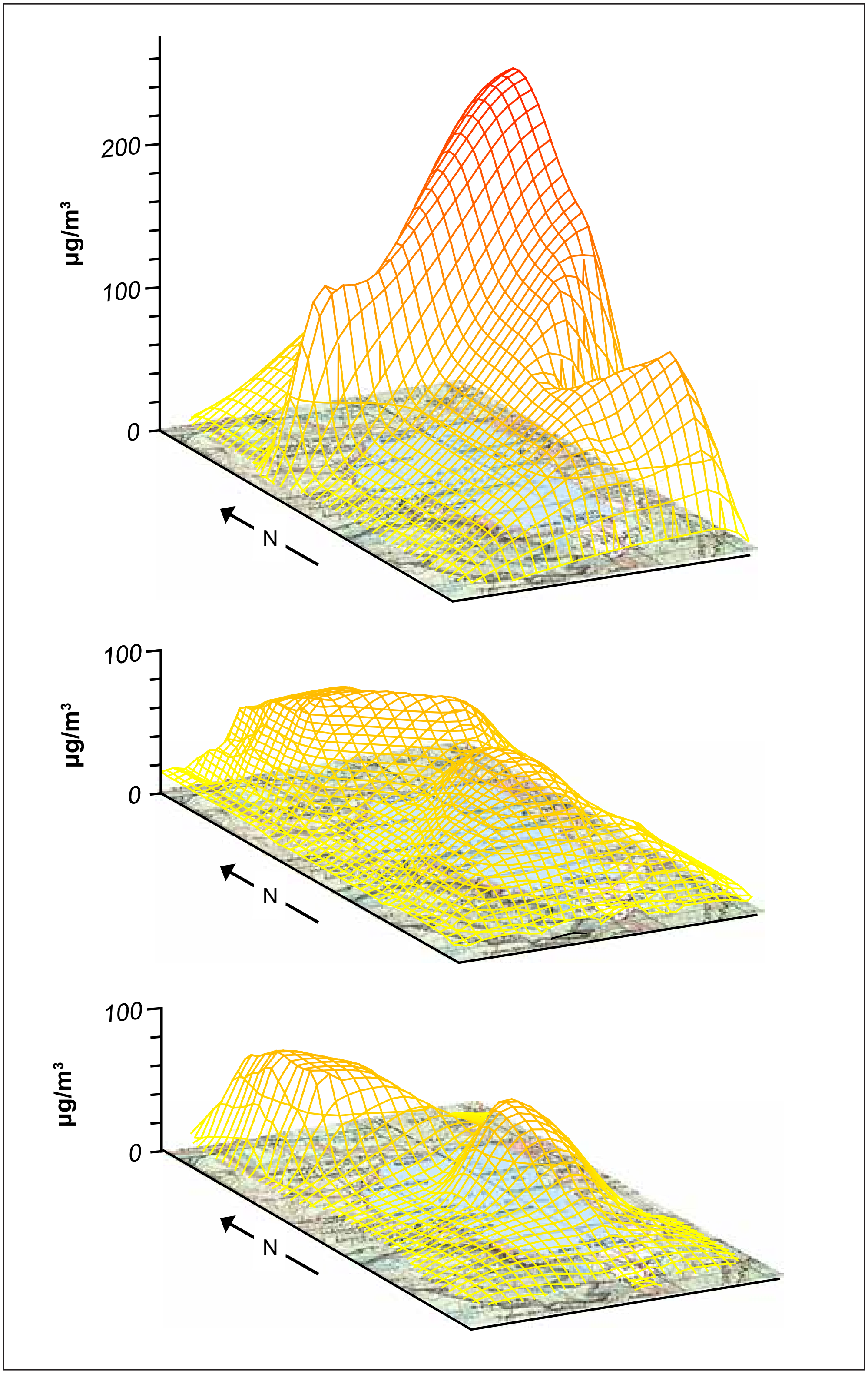

Figure 3.6—Example of Lake Tahoe Atmospheric Model prediction of the evolution of $PM_{2.5}$ from forest fire smoke for 3 days during the Ward Creek prescribed burn. The z-axis represents $PM_{2.5}$ concentrations in µg/m^3. The bottom graph is day 1 and the top graph is day 3.

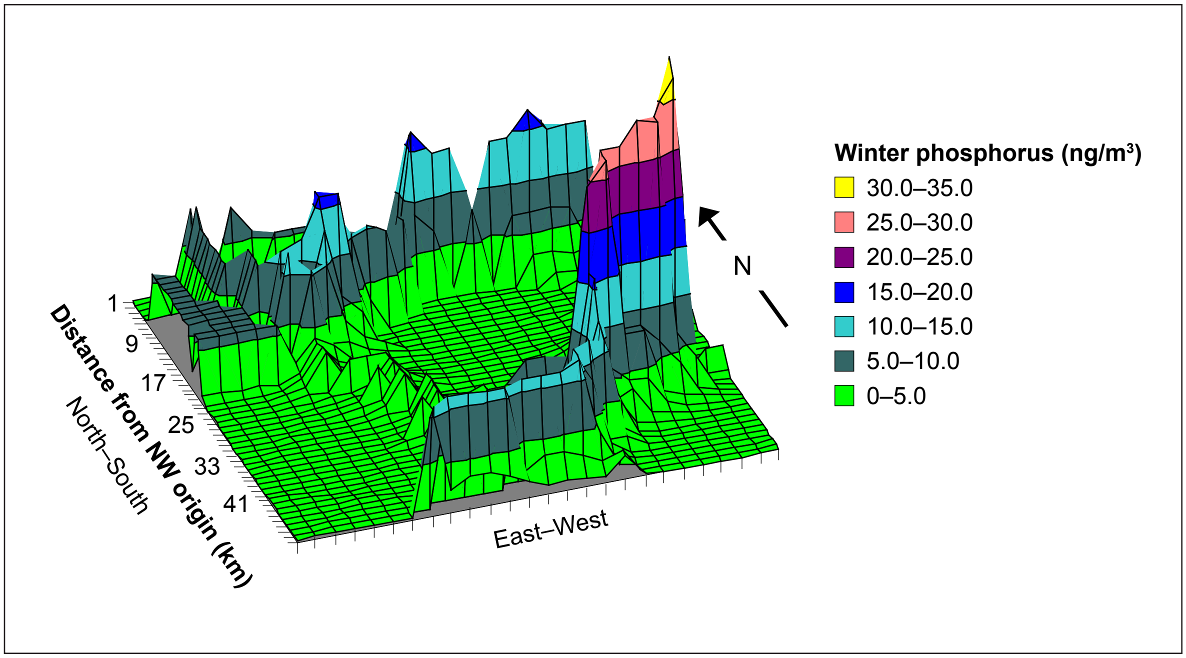

Figure 3.7—Lake Tahoe Atmospheric Model extended to include phosphorus concentrations (ng/m^3) around and over Lake Tahoe. Courtesy of UC Davis Delta Group.

Knowledge Gaps

- Currently, the only modeling system developed for use in the basin is the LTAM, which is a heuristic gridded model that allows the merging of the limited amounts of meteorological, aerosol, and gas data into a mass conserving spatial distribution. No information on wet deposition or chemical transformations is included. Thus, it is no better than its limited data set, and is sensitive to gross assumptions.
- Additional limitations of the LTAM include limited grid size (2.59 km^2); includes only first-order deposition; and does not handle multiple inversion layers, including their impact on upwind sources.

Research Needs

- Examine the literature for preexisting models that could be adapted to Lake Tahoe use. These models may supersede the LTAM.
- If continued use of the LTAM is going to occur, then the following improvements are recommended:
  - Increase the spatial resolution of LTAM and add a near-roadway program model for the cells that straddle lakeside roads.
  - Add the information from LTADS study into the LTAM or any future modeling system.

    - Add the LTADS aerosol data from the upwind sites into the LTAM or any future modeling system.
    - Improve the deposition module in LTAM.
    - Compare the LTAM sediment and P-deposition predictions with on-lake aerosol data from LTADS.
    - Develop specific features in the model to address the potential effects of air pollutant control options that are spatially located within the basin.
- Perform sensitivity analyses with the LTAM or any future modeling system to evaluate management strategies.

Impact of Fire on Air Quality

Atmospheric pollutants that contribute to overall air quality at Lake Tahoe derive from both natural and anthropogenic sources. For instance, wildfires, volatile organic compound emission from trees, and wind-blown dust from natural landscapes all are natural phenomena. On the other hand, automotive and industrial pollutants, prescribed fire smoke, and human-caused wildfire smoke all derive from anthropogenic sources. Fire sources can be broken into six forest regimes and one urban regime:

- Forest regimes:
    - Natural wildfires.
    - Wildfire type 1—surface burn—close to natural wildfires, sometimes occurs after prescribed fires burn out of prescription.
    - Wildfire type 2—passive crowning fire (e.g., the 1992 Cleveland wildfire at the maximum impact site).
    - Wildfire type 3—active crowning wildfire (e.g., as in the early phases of the Oregon Biscuit complex fire).
    - Prescribed fire type 1—pile burn, PF1 in which there is lofting of smoke (h) to greater altitudes ($0.1 < h < 0.5$ km).
    - Prescribed fire type 2—surface burn, PF2, in which there is no lofting of smoke (h) ($0 < h < 0.1$ km), as in the 1992 Turtleback Dome (Yosemite National Park) prescribed fire.
- Urban regime:
    - Residential wood fires.

It is surprisingly difficult to establish the effect of forest regime smoke sources on Sierra Nevada air quality. Smoke has a visual impact out of proportion with the mass of smoke present, so that smoke levels must be extreme before the record

Courtesy of University of Nevada Cooperative Extension

Smoke plume from the 2007 Angora wildfire in South Lake Tahoe, California.

of particulate mass reflects a major impact. Yet the 24-hour federal particulate standard for PM_{10} is not violated until visibility drops to about 3.2 km. Most of the air particulate sampling in the Sierra Nevada measures only PM_{10} mass, and thus is of limited use in identifying small and moderate smoke impacts. These sites only operate on a 1-day-in-6 cycle, and due to urban locations, are of little use to establish nonurban smoke levels. Further, the data on how many acres are burned each day from either wildfires or prescribed burns is often difficult to access. Meteorological measurements in the mountains are scarce, and terrain effects are major.

The IMPROVE (Interagency Monitoring for Protected Visual Environments, Malm et al. 1994) database is useful in several regards. The measurements are $PM_{2.5}$, a better match to the size of smoke particles. The sites operate Wednesday and Saturday, in nonurban, nonvalley locations, and have full meteorology, chemical, and optical analysis. However, in 2002, there were only two such sites in the Sierra Nevada: Sequoia and Yosemite National Park. Fortunately, the paired stations at Lake Tahoe (Bliss and South Lake Tahoe), operated for the TRPA using full IMPROVE protocols, provide a very important third site, as well as an invaluable nonurban to urban comparison. Finally, data are extended by using similar sites in the Cascade and San Bernardino Mountains. This data set is used for long-term data on Sierran smoke, supplemented by local studies.

Impacts from "natural" wildfires are not seen today since this regime, (numerous small, noncrown fires in summer and early fall) ended in the mid 19th century. The expected air quality in the Tahoe basin under conditions of "natural" wildfires is for spotty but persistent smoke in relatively low concentrations around the basin. This regime has been modeled in LTAM (e.g., see the discussion in "Air Pollutant Emission Inventories" section), based upon the fire scars on Tahoe basin trees that yielded an average of 30 burned acres per day. The model results suggest the pollution maximum over the lake each morning did not exceed present (65 $\mu g/m^3$) and proposed (35 $\mu g/m^3$) $PM_{2.5}$ mass standards (fig. 3.8).

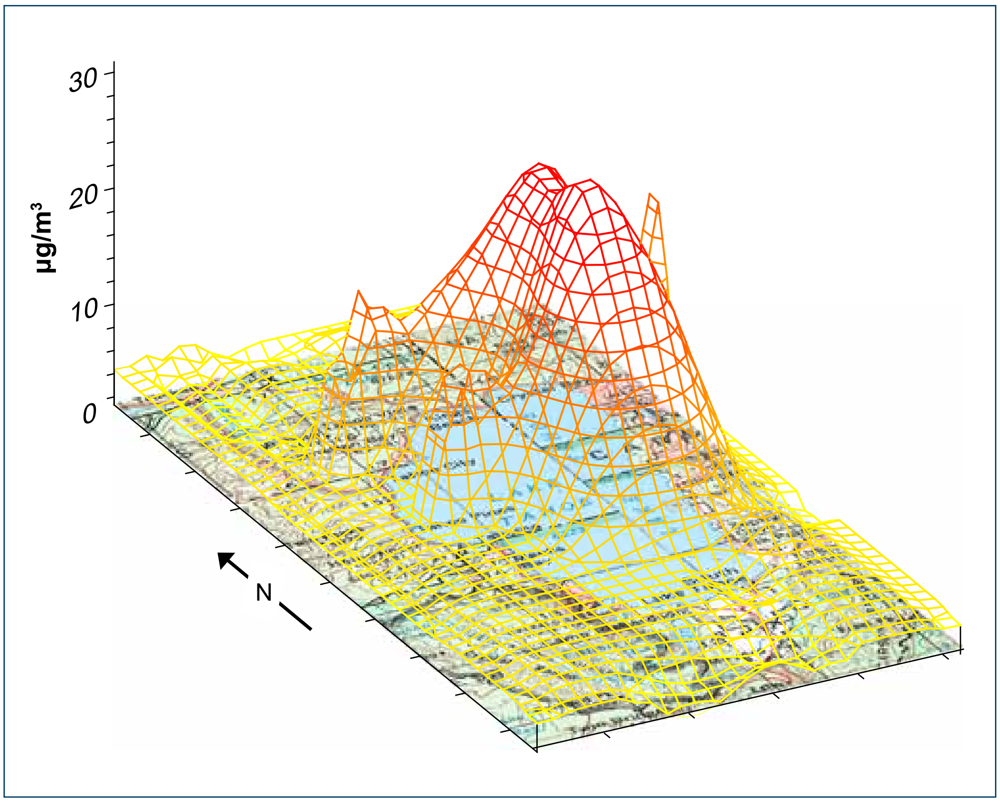

Figure 3.8—Lake Tahoe Atmospheric Model output for $PM_{2.5}$ concentration distribution ($\mu g/m^3$) in the Lake Tahoe basin (underlying map) from historical fire situation based on a 24-hour average.

Present day wildfires are often human caused and always enhanced by humans owing to fuel buildup. They are infrequent, but can and have had massive impacts on the Lake Tahoe basin, degrading visibility and probably violating state and federal air quality standards (based on Truckee data). However, the 202 300-ha Biscuit Fire in Oregon, which during many days was an actively crowning fire, delivered a maximum of only 20 $\mu g/m^3$ ($PM_{2.5}$) into the Tahoe basin in August 2002. This was still adequate to largely obscure the visibility across the long axis of Lake Tahoe.

There are relatively few air quality data on the impacts of prescribed fire beyond the obvious smoke plumes seen near such burns. There are good reasons for this lack of data. First, filter measurements near a prescribed burn will often clog with the vapors from the burn. Second, it is difficult to obtain a close-in representative sampling site, especially when pile burns push the smoke up through the forest canopy.

Analysis of aerosol data from several sites in the Sierra Nevada indicates that the most severe impacts on air quality occur from large wildfires, but shows little effect of controlled fires at remote locations (Cliff and Cahill 2000). In addition, relatively low levels of PM are seen during the subsequent fall season when the majority of agricultural waste burning occurs in the San Joaquin Valley as well as controlled burning in nearby forests for fire suppression and silviculture.

Current data suggest controlled forest burns are not a major source of particulate mass in populated areas of the Sierra Nevada, as compared to residential wood combustion and campfires (Cliff and Cahill 2000). Large wildfires produce severe short-term impacts on air quality. Prescribed or controlled burns are more common, but the amount of materials burned are more modest, and the measures to limit human smoke impacts are generally quite effective, leading to very low contributions to PM_{10} particulate loading in inhabited areas. Thus, it would appear that prescribed fires are usually performed in such a way as not to cause a substantial threat to regional air quality as measured by fine particulate mass. The obvious exception is for some local visibility reduction, but this would be offset by improved air quality from decreasing the fuel accumulation and resulting impacts of potential major wildfires that may occur.

The best data on the impact of residential wood burning come from the TRPA sampling site at South Lake Tahoe. Based on these data and the results from D.L. Bliss State Park, located in a largely undeveloped area on the west shore of Lake Tahoe, it appears that residential wood combustion is a major source of PM in South Lake Tahoe. The only period in which occasional elevated levels of smoke are detected at both sites, indicating a source outside the basin, is the late fall when large amounts of cropland are being burned in the Sacramento Valley and controlled burning in the surrounding national forests is at its peak. But even in these conditions, the smoke levels are far less than the winter peaks in South Lake Tahoe (roughly 20 percent of the total observed PM), and of much shorter duration.

Emissions from fire can impact lake clarity. Fires can be a source of P (Turn et al. 1997), but this appears to be very sensitive to the conditions in the burn as well as the type of vegetation. However, if there is extreme uplift of a catastrophic wildfire (active crowning), the P gets sucked up into the smoke plume and can be deposited many kilometers away.

Smoke from prescribed fire pile burning off Highway 267, north shore, Lake Tahoe.

In summary, resolution of the questions regarding the impact of smoke in the Sierra Nevada mountains is difficult based on limited composition, size, and transport data for this source. In the Lake Tahoe basin, knowledge of meteorology for much of the basin as well as deposition to the lake surface is lacking, although the LTADS data set should help. Furthermore, few measurements have been made of emissions from wildfire and prescribed fires for both mass and chemistry. The LTAM would greatly benefit from increased knowledge of these parameters. Nevertheless, smoke from fires remains a major factor in visibility degradation in the Lake Tahoe basin (Molenar et al. 1994). Large wildfires are also reported to impact Lake Tahoe water quality by causing algal blooms in the lake (Goldman et al. 1990), although the impacts may be short-lived (TERC 2008). The impact of prescribed fire, however, is relatively unknown, but probably minor based on historical levels.

Knowledge Gaps

- Understanding of how changes in prescribed fire regimens on the western slope of the Sierra Nevada will impact Lake Tahoe basin smoke levels.
- Understanding of the uncertainty associated with the impact of out-of-basin wildfires on Lake Tahoe basin visibility.
- How different methods of prescribed fire within the Lake Tahoe basin impact basinwide visibility and air quality.
- A better understanding of the impacts of fires in general on deposition of particles and nutrients onto Lake Tahoe.
- The contribution of in-basin residential wood burning versus in-basin prescribed fires.
- The impact of fires on human health and emissions of toxic species such as polycyclic aromatic hydrocarbons (PAHs).
- Measures to effectively improve visibility and reduce deposition in smoke-impacted scenarios.
- What measures can effectively be taken outside but upwind of the Lake Tahoe basin to improve visibility and reduce deposition and air quality impacts in smoke-impacted scenarios in the basin?

Research Needs

- Gather more detailed estimates of the frequency and location of prescribed fires along with measurements of prescribed fire aerosols by size, type, and composition by fire type (e.g., pile burn, or surface burn) and meteorology, and use cameras for vertical development of smoke, are recommended.
- Use impactors and continuous PM monitors (as opposed to filters) to quantify PM levels and the filter artifact from semivolatile organics in near-fire analyses.
- Measure the elemental carbon/organic carbon ratio as a function of the type of fire and fuel.
- Assess the impact of fires on air quality, deposition, and human health.
- Evaluate the effects transport of prescribed fire aerosols on the western slope of the Sierra Nevada have on Lake Tahoe, including nutrient deposition onto the lake.
- Evaluate the impact of wildfires by season, type, and transport, including nutrient deposition onto Lake Tahoe.

- Better establish and quantify the role of residential wood smoke in winter conditions.
- Develop advanced measurement (e.g., satellite data) and visualization capabilities to aid with the assessment of fire impacts on air quality.

Near-Term Research Priorities

Air quality (AQ) near-term research priorities are as follows:

- (AQ1) Improving air quality and meteorological monitoring in the basin is highly recommended. The first step to addressing current deficiencies would include development of a comprehensive monitoring plan for the basin that addresses the criteria pollutants (covered under the NAAQS) and species impacting human and ecosystem health (including water clarity and forest health), along with the requisite spatial and temporal distribution of the measurements. Once this plan is prepared, sampling locations can be chosen and appropriate air quality and meteorological sensors can be deployed.
- (AQ2) Many of the key chemical species and physical parameters leading to secondary pollutant formation and/or deposition to the lake are not currently measured. Air quality measurements of key species under a range of meteorological conditions and averaging times are recommended following the development of a monitoring plan (see air quality monitoring description above). Parameters to measure include measurements for NO_x, NH_3, HNO_3, size-segregated aerosol mass, particle number and particle size distribution, and aerosol chemical composition. Once these data are obtained, it will be possible to assess atmospheric impacts and air pollutant trends. This information will also provide the necessary input for developing an understanding of the processes controlling air quality and atmospheric deposition in the basin.
- (AQ3) The only model adapted for use in the basin is the LTAM, a heuristic model that is based on statistical input. An appropriate air quality model incorporating physical processes needs to be developed that can utilize the full suite of meteorological, chemical, and particulate data. This will enable managers and scientists to better assess air pollutant trends, estimate impacts, and support the development of effective regulations that will assist in meeting air quality and other environmental goals.
- (AQ4) Atmospheric deposition to the lake is the major source of nitrogen and a substantial source of phosphorous and particulate matter. There is, however, significant uncertainty in deposition flux estimates. To reduce

this uncertainty, conduct focused studies (gradient or eddy-correlation studies, along with measurements of key species) of the sources and pathways of particle deposition to better inform models and restoration efforts.

- (AQ5) Mobile source emissions are a major source of pollutants in the basin. Improving our understanding of mobile source emissions would include obtaining Tahoe-specific vehicle model year distributions, emission factors, and activity data for use in mobile source emission factor models. These results will reduce the uncertainty in the emissions inventory and enable regulators to develop more effective strategies to reduce pollution in the basin.

English Equivalents:

When you know:	Multiply by:	To get:
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles
Hectares (ha)	2.47	Acres
Square kilometers (km^2)	.38	Square miles
Micrograms (µg)	3.527×10^{-8}	Ounces
Micrometers (µm)	3.937×10^{-6}	Inches
Tonnes	2,204.6	Pounds

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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.

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

Water Quality Conceptual Model

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

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

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

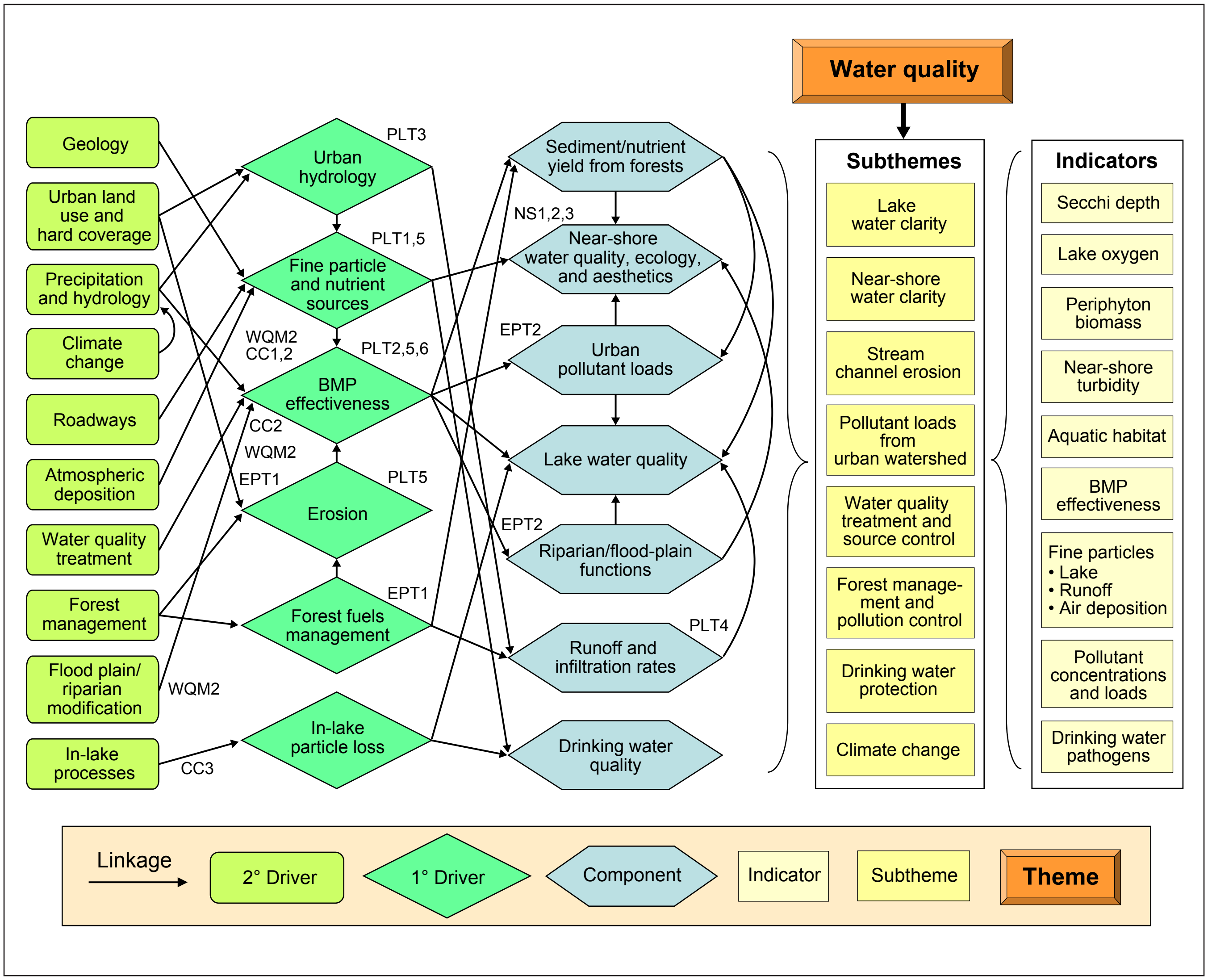


Figure 4.1—Conceptual model for Lake Tahoe water quality subthemes. This model focuses on the pollutant pathway for fine sediment particles (<20 µm) and nutrients (nitrogen and phosphorus). Key processes in this pathway include source identification, transport within the watershed, control and abatement,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

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

Lake Tahoe Water Clarity

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

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

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

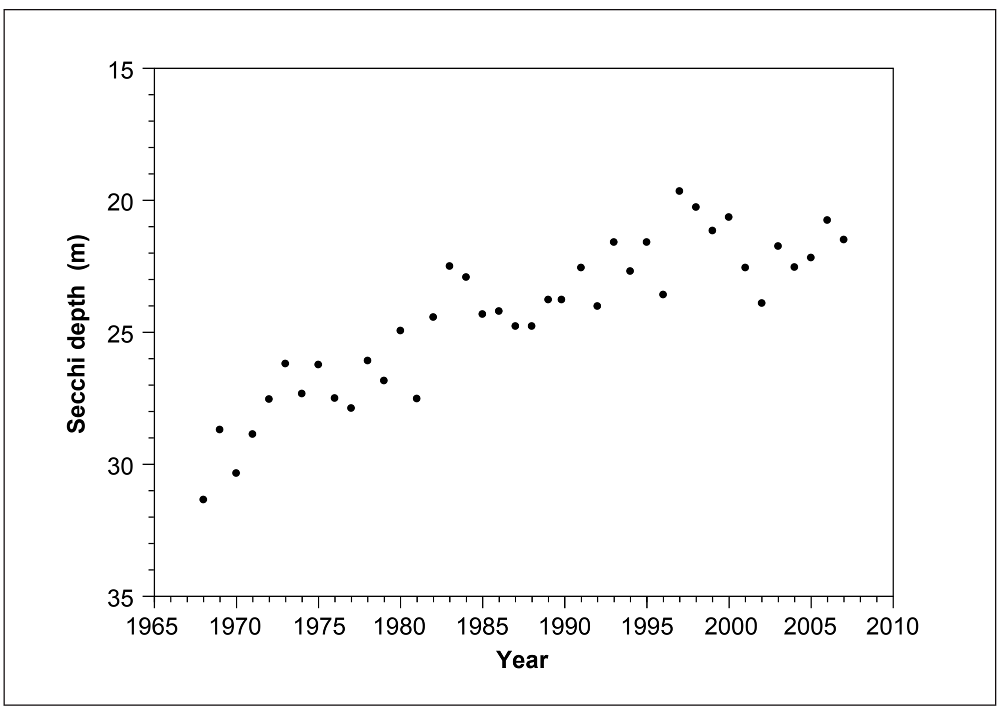


Figure 4.2—Long-term Secchi depth data from Lake Tahoe. Each value represents the annual, time-weighted average based on approximately 25 measurements per year. Date collected by Tahoe Environmental Research Center, University of California Davis.

Jim Markle

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

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

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

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

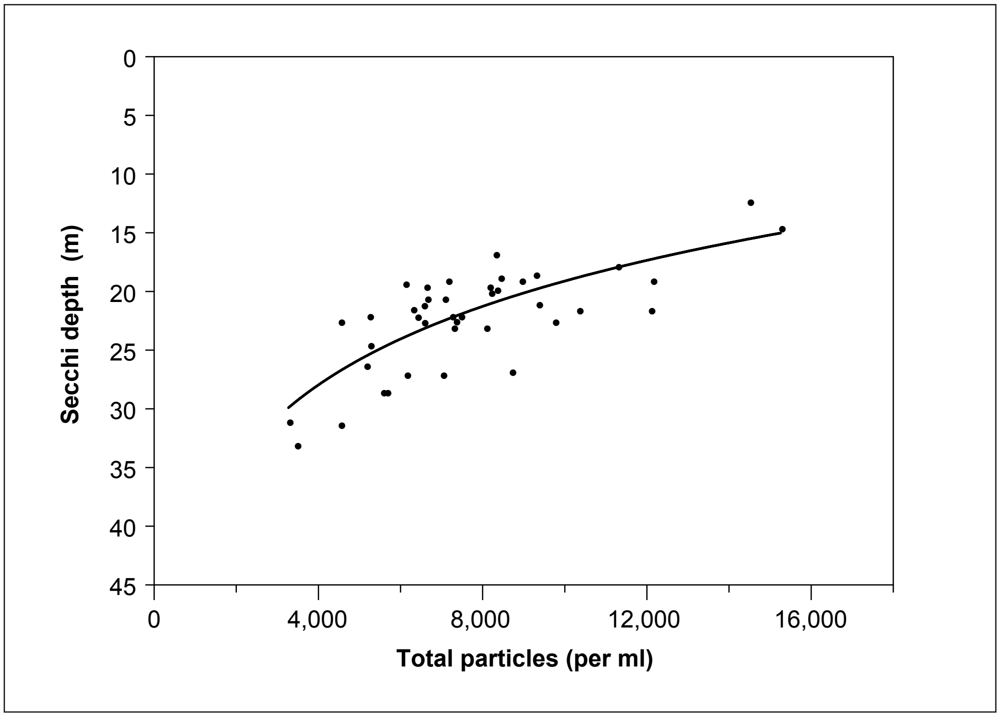


Figure 4.3—Relationship between in-lake particle number and Secchi depth (from Swift 2004). $P < 0.001$, $r^2 = 0.57$. Each point represents a single measurement of Secchi depth and particle concentration.

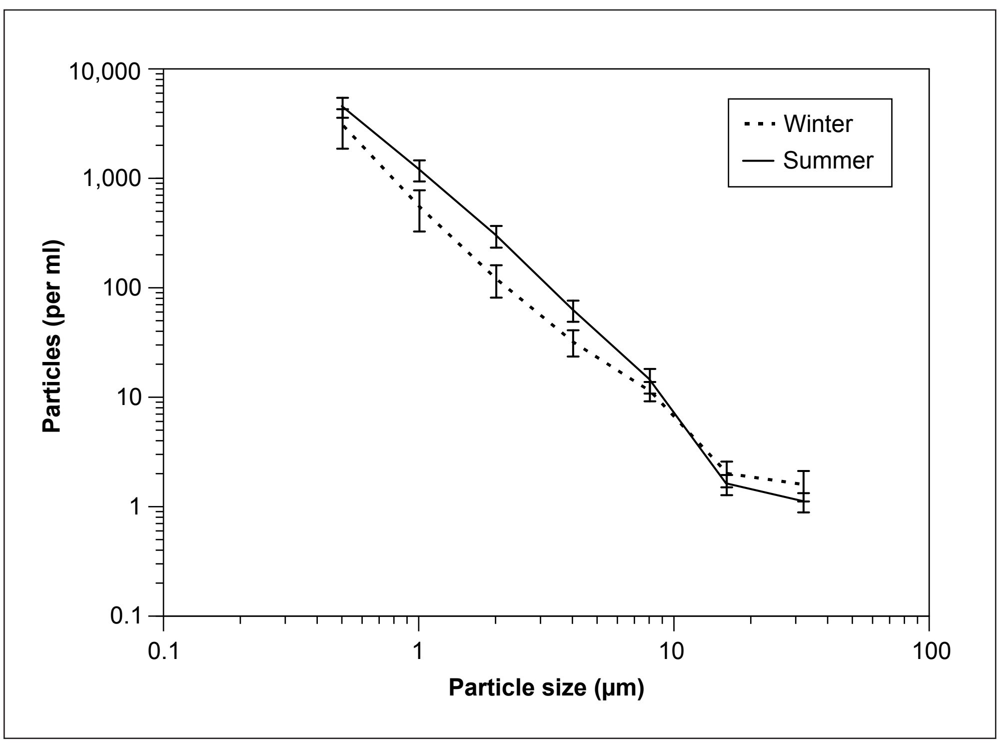


Figure 4.4—Particle size distribution in Lake Tahoe water samples showing dominance of particles <5 µm in diameter (from Swift et al. 2006).

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

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

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

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

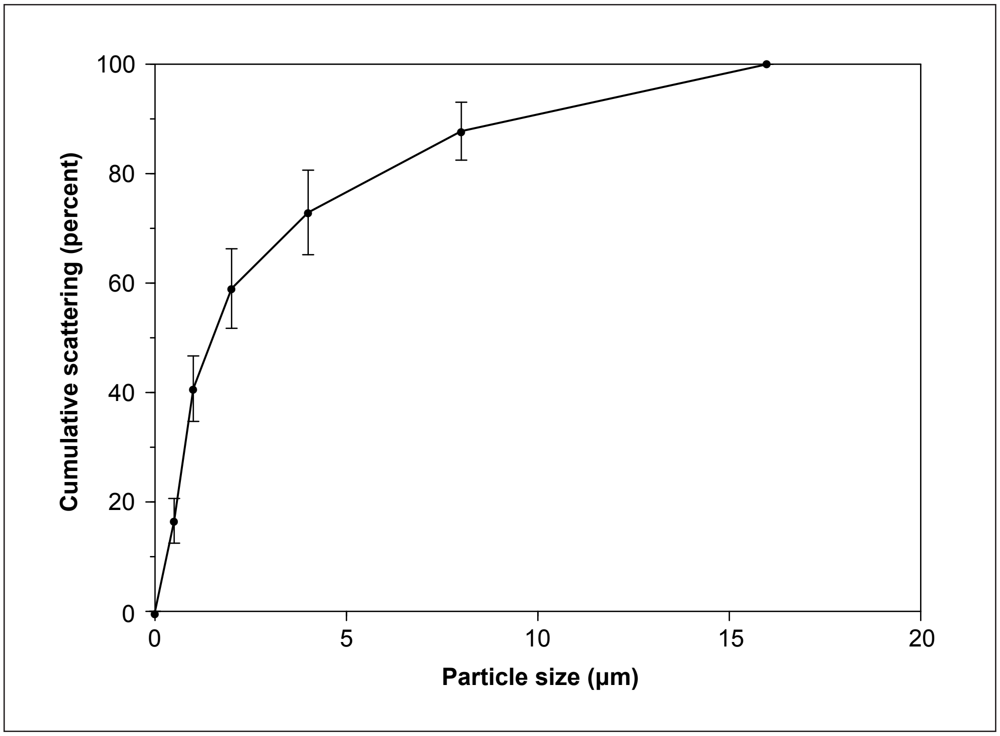


Figure 4.5—Cumulative contribution to the scattering coefficient, b_{ip}, for each of the particle size ranges. The influence of the 16 to 32 µm size range was negligible and is not included in this plot. The full 0.5 to 16 µm size range shown represents the following individual size bins, 0.5 to 1,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

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

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

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

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

Knowledge Gaps

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

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

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

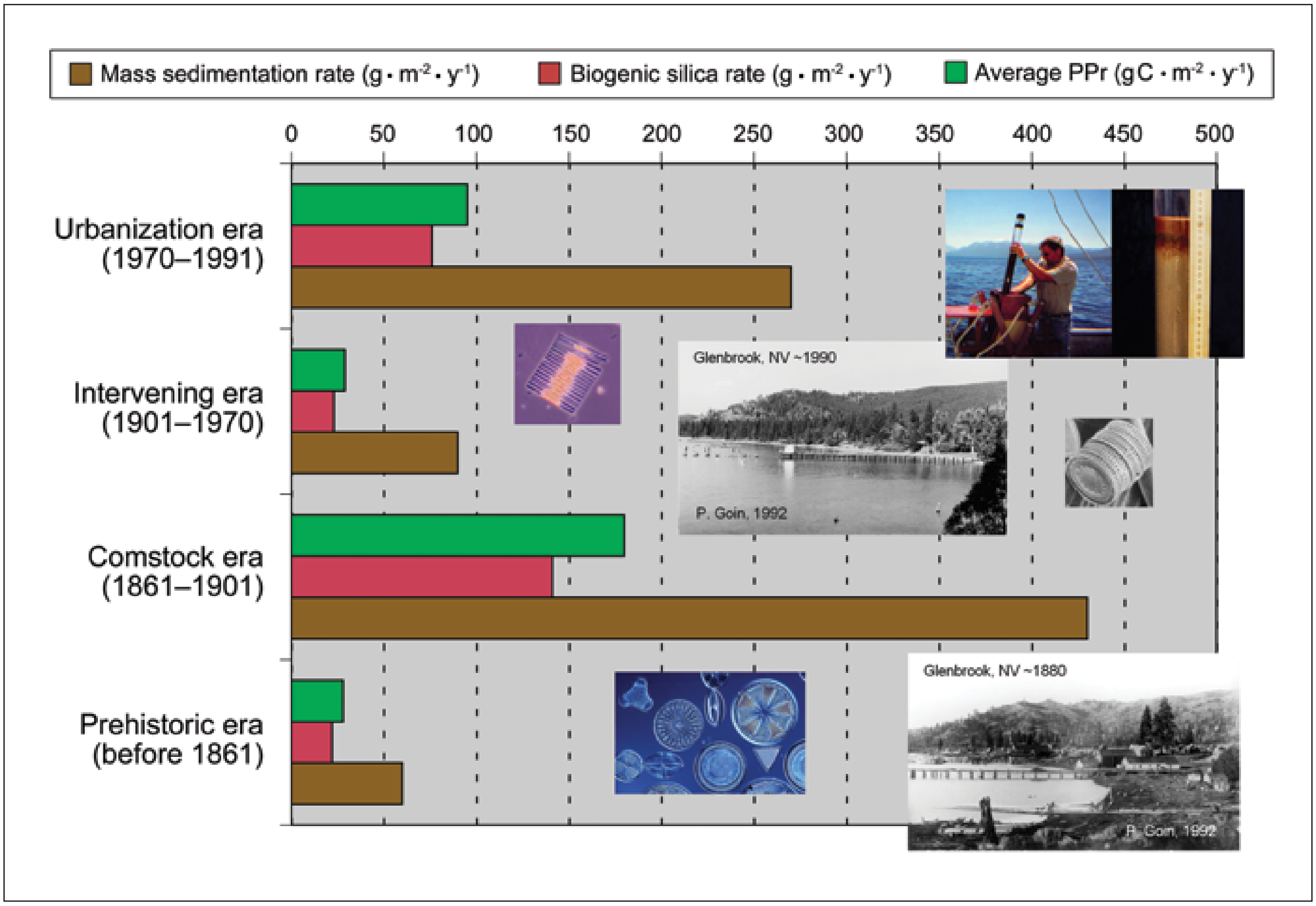


Figure 4.6—Summary of paleolimnologic studies that reconstruct the recent water quality history of Lake Tahoe (from A. Heyvaert, Desert Research Institute). Mass sedimentation includes all material, both biogenic and abiotic. Biogenic silica is derived primarily from diatoms and provides an estimate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

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

Research Needs

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Lake Tahoe Near-Shore Water Quality

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

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

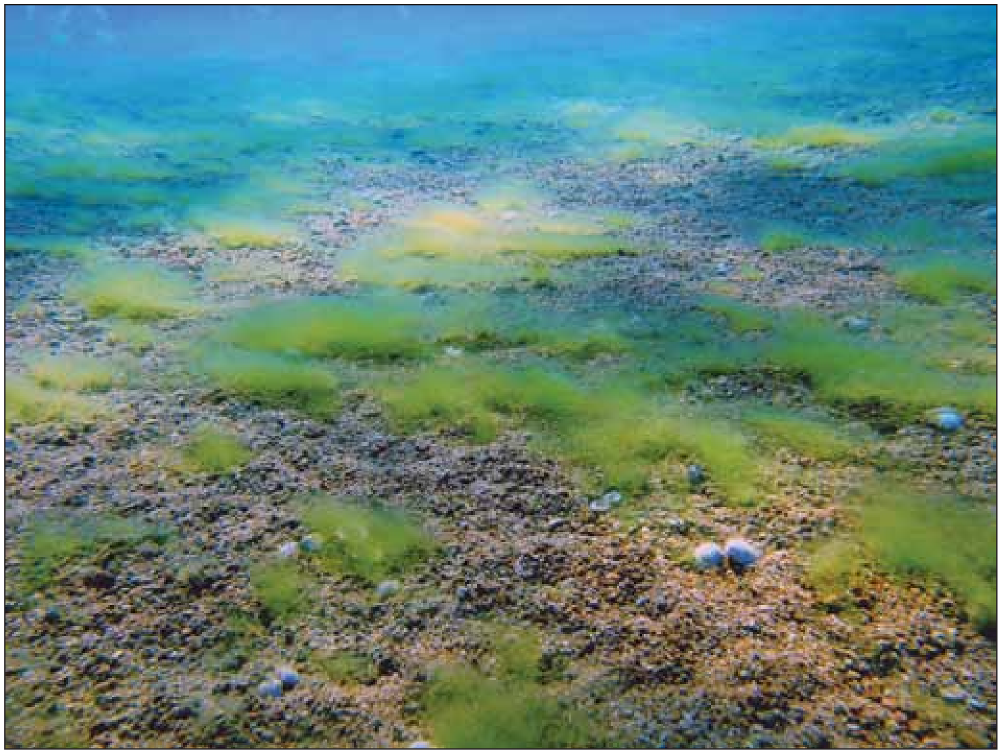
Jim Markle

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

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

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

Brant Allen



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

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

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

Knowledge Gaps

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

- The lack of baseline data needed to develop a comprehensive understanding of the near-shore ecosystem that can inform management strategies and support environmental thresholds. The existing patchwork of studies investigating near-shore processes and stressors has not been sufficient to sustain a consistent baseline data collection effort. Continued research and monitoring is necessary to assess long-term trends, to better understand near-shore processes, and to develop quantitative near-shore water quality standards. Data from such a program are invaluable and could be used to inform the following knowledge gaps:
    - Response of the near shore to watershed restoration and management activities. It is unknown if the reduction of nutrient and sediment sources currently being planned and implemented will mitigate near-shore impairment. Monitoring of near-shore characteristics is needed to better understand the effectiveness, results, and potentially unintended consequences of onshore treatments (e.g., stormwater infiltration basins installed near the lake shore).
    - The potential direct and indirect effects of future near-shore development and boating scenarios (e.g., piers and buoys) on near-shore ecology and water quality.
    - The impacts that changing/managed lake level has on near-shore water quality, periphyton communities, and habitat.
    - The information base agencies need to establish informed water quality standards, and environmental thresholds and indicators that will be protective of near-shore water quality and aesthetics.
- It is important to recognize and improve our understanding of the roles that spatial variation plays in near-shore processes. The spatial variability of conditions in the near shore is very complex owing to the interactions among a suite of land-based and lake-based processes. The near shore can be roughly divided on the basis of depth (eulittoral or splash zone and sublittoral) and urban versus undeveloped. Near-shore habitats also differ around the lake owing to factors such as embayments, marinas, open water, and bottom substrate type. Lastly, the near-shore zone is also impacted by the variability found within adjacent onshore watersheds (e.g., soils and land use) and the circulation and mixing patterns with the deeper waters of the pelagic zone. Examples of existing knowledge gaps include:

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

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

Research Needs

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

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

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

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

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

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

- 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., $<16\ \mu m$).

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).

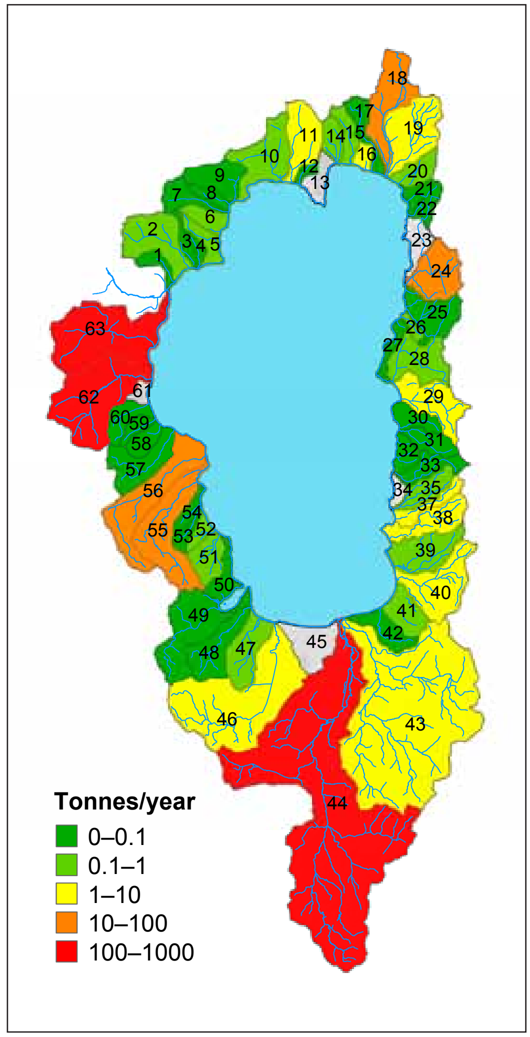


Figure 4.7—Fine-sediment loadings from streambank erosion (from Simon 2006).

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

[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

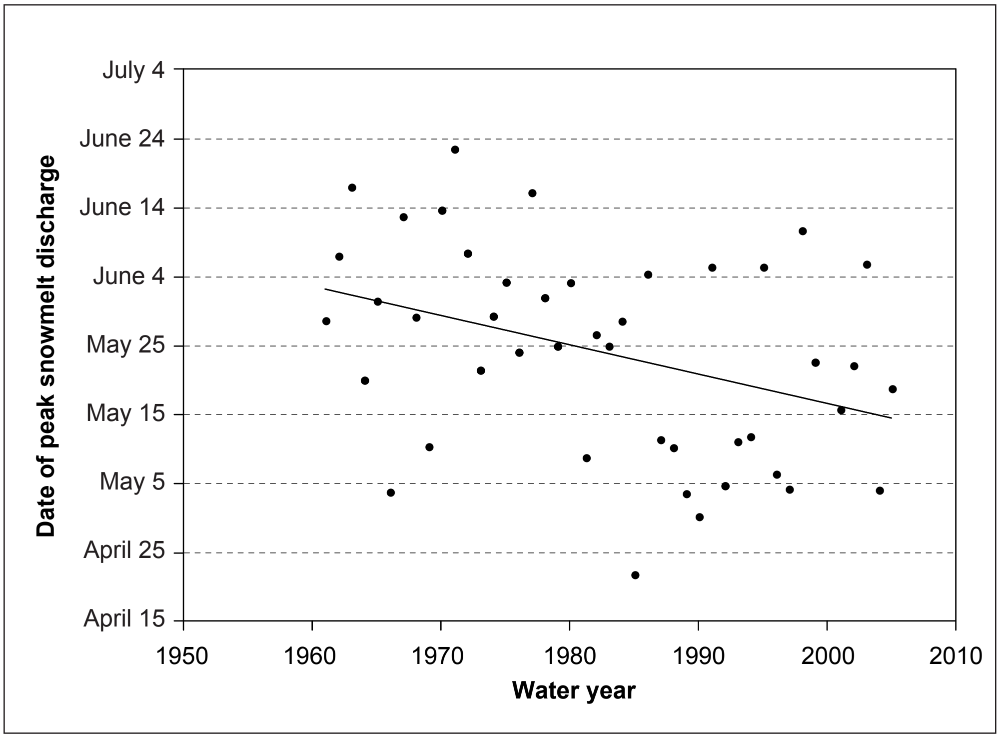


Figure 4.8—Average date of snowmelt peak discharge, for Ward, Blackwood, Third and Trout Creeks, and the Upper Truckee River (from R. Coats). $P = 0.01$, $r^2 = 0.14$.

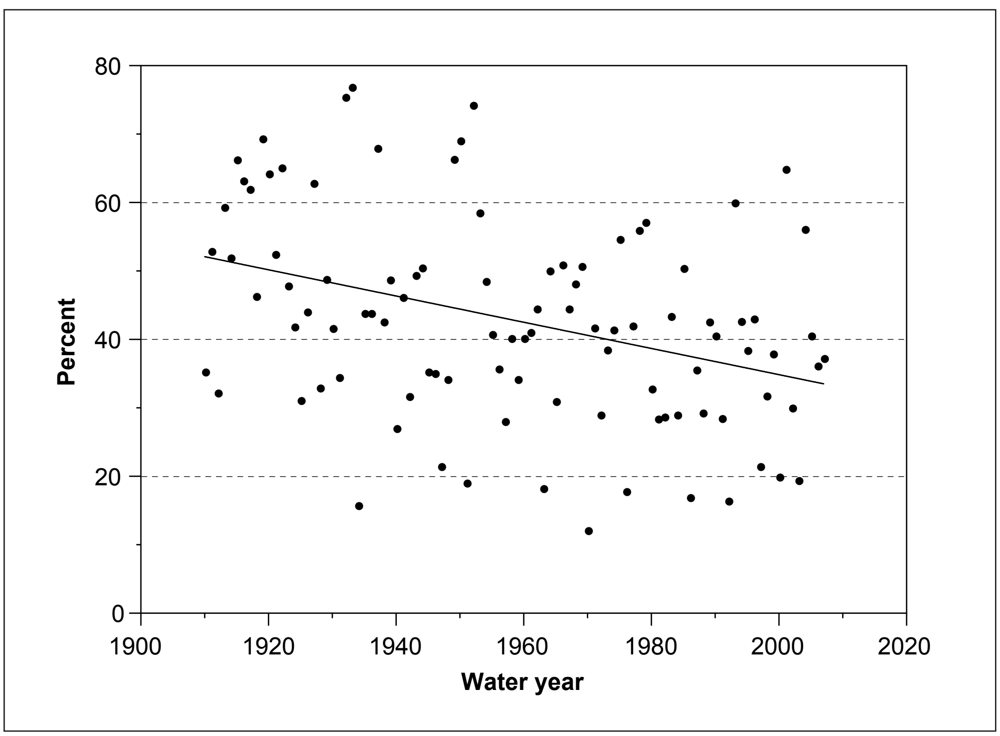


Figure 4.9—The percentage of total annual precipitation falling as snow at Tahoe City, CA (from R. Coats). $P < 0.001$, $r^2 = 0.13$.

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.

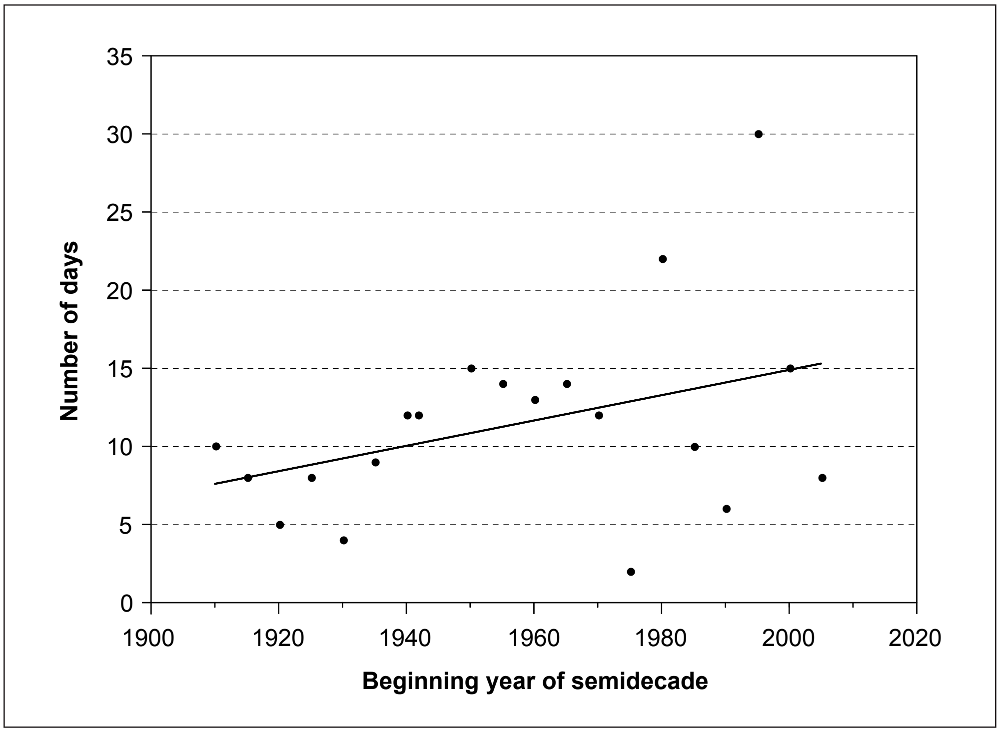


Figure 4.10—Number of days per semidecade with daily rainfall exceeding the 95th percentile daily amount (from R. Coats). $P < 0.1$, $r^2 = 0.14$.

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.

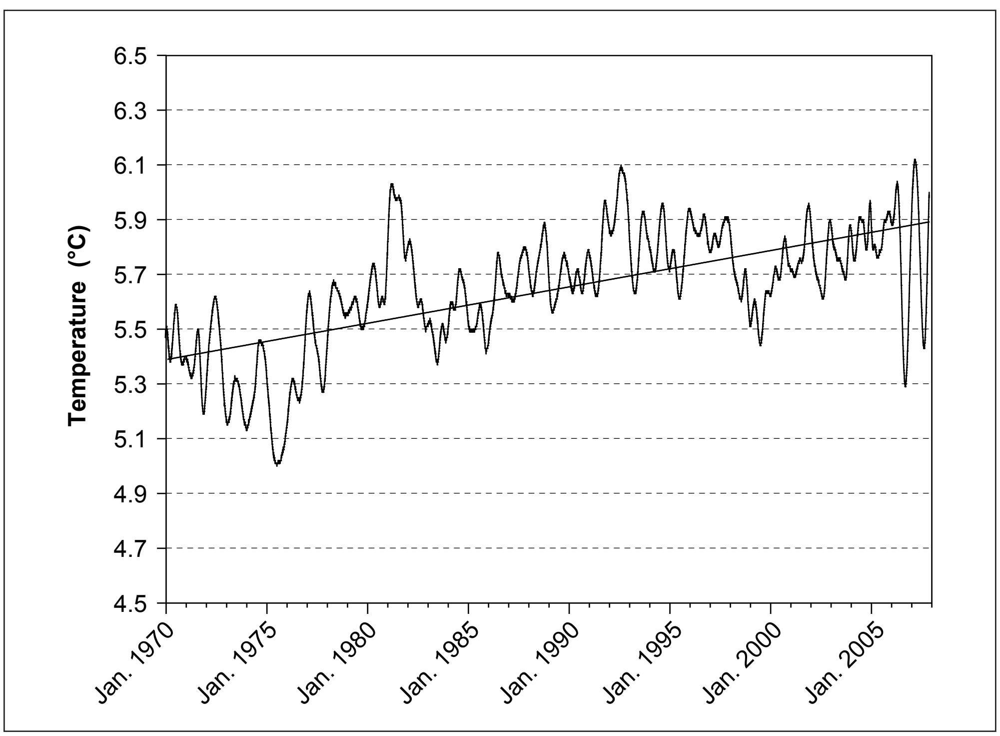


Figure 4.11—The average daily temperature of Lake Tahoe, as deviation from seasonal norm (from R. Coats). P = 0, $r^2 = 0.43$. Average temperature values were calculated as the volume-weighted mean of daily measurements made at 11 depths from the surface to 450 m (near-bottom).

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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Go to Part 3 (Chapters 5, 6, and 7)

Chapter 5: Soil Conservation[1]

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Introduction

Soil conservation as a research and management theme can mean many things to agencies and the general public. The historical concept was rooted in agriculture and agricultural production. Indeed, in 1957 the "modern" objectives of soil and water conservation identified by Stallings (1957) were to:

- Reduce the accelerated loss of soil that attends the use of land for agricultural crops.
- Find ways of reclaiming severely eroded land.

Soil conservation today conveys a much broader concept, and conservation management strategies go well beyond simply the protection of soil from processes of physical erosion to now encompass the protection and enhancement of overall soil quality. Improved soil quality prevents land resource degradation by resisting erosion and invasive species, strengthening the soil's capacity to support plant growth, favoring species diversity, preventing environmental contamination, and conserving water (Brady and Weil 2008).

The intent of this chapter is to identify the most pressing management questions, uncertainties, and pertinent research needed to address a wide spectrum of plant-, soil-, and water-related issues in the Lake Tahoe basin. In developing the organization and content for the soil conservation theme, the original outline considered a number of topical subtheme areas such as soil ecology, soil erosion, etc. However, input received from Tahoe Science Plan participants indicated that they were interested in cross-cutting issues rather than the topic-specific categories originally presented. In response, suggestions from the workshop were grouped into four new subthemes considered by the constituency to be of high priority and in need of resolution relative to current management concerns.

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We provide a brief introduction of each subtheme, which includes a description of the subtheme, what we know about it, and its relevance (perceived or real) to the overall science theme area and management strategies in the Lake Tahoe basin. In the subsection entitled "Knowledge Gaps" we provide a problem statement that describes the general issue, then in bullet format identify specific aspects relative to that issue where we recommend enhancing the knowledge base. The subsection entitled "Research Needs" presents a nonprioritized list of identified research topics.

Beyond the specific discussions of subthemes, we provide a conceptual model and identify a prioritized listing of the three most immediate near-term soil conservation research priorities within each subtheme.

Conceptual Model

Figure 5.1 illustrates four primary tiers of hierarchy: theme area, subthemes, components (response-based ecosystem components), and drivers (e.g., stressors, management activities, other external forces). The following subthemes were adopted as the primary categories or conditions of interest to agencies and the public:

- Key soil properties and conditions.
- Development and application of predictive models.
- Effects of climate change.
- Policy implications and adaptive management strategies.

A number of coupled processes were next identified as a set of complex **response indicators** potentially affecting one or more aspects of the four subtheme conditions. These **interactive components** are used to identify and express the degree of consistency with desired conditions and include (1) changes in soil physical and chemical properties, (2) altered hydrologic function and the corresponding effects on erosion, (3) nutrient cycling and discharge water quality, (4) the collective and independent short- and long-term effectiveness of best management practice (BMP) strategies, and (5) the evaluation of current and future policy thresholds in the context of scientific information and an ever-expanding knowledge base. Finally, expected linkages between primary and secondary drivers are presented as **agents of change**, natural or human caused, which can affect the condition of the components specified and their indicator values.

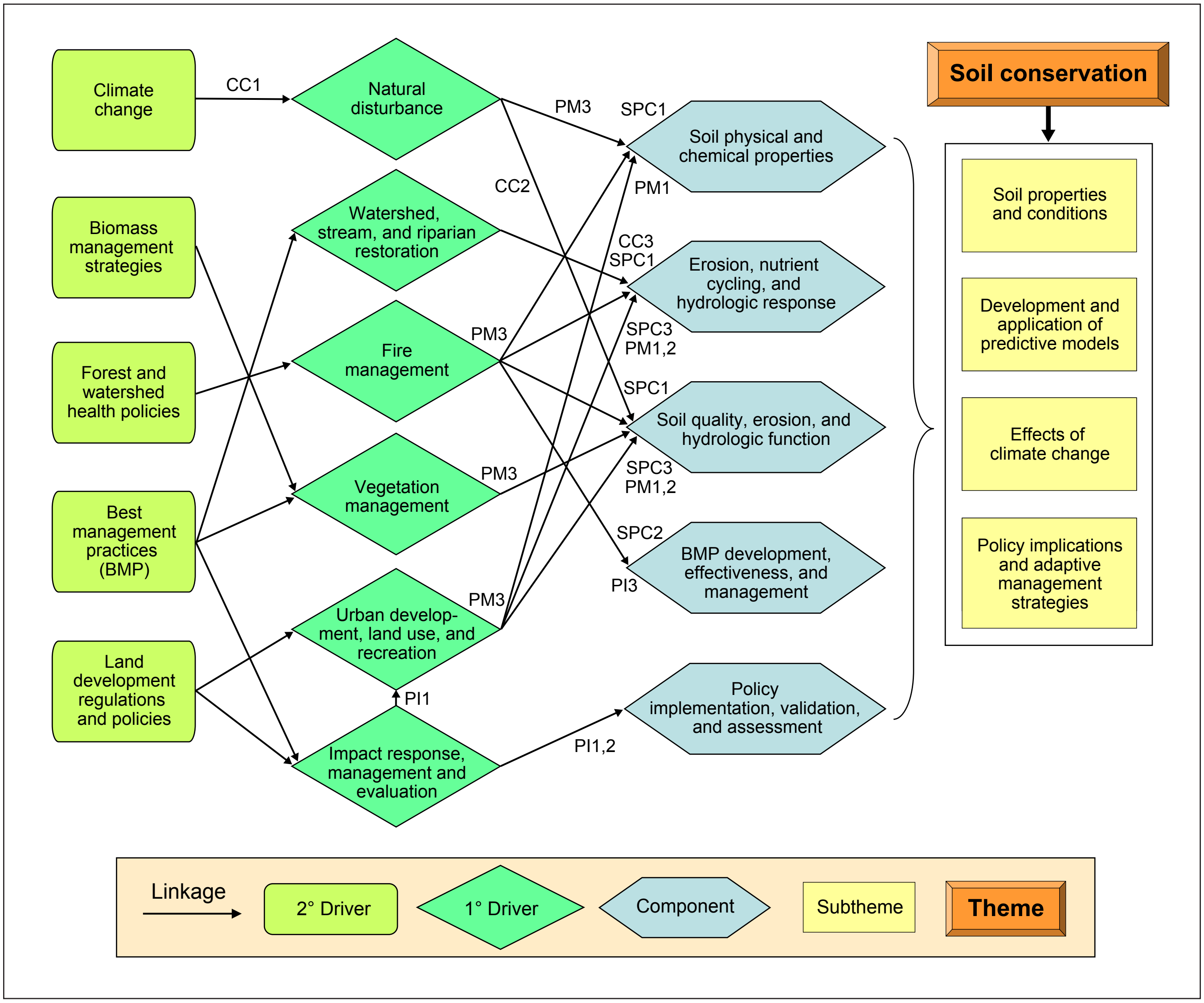

Figure 5.1—Conceptual model illustrating how the Soil Conservation research theme system is perceived, its scope, the primary factors, and how they relate to one another. Near-term priorities are indicated by alpha numeric symbols (e.g., CC1, PM3) and correspond to the descriptions presented later in the chapter.

Key Soil Properties and Conditions

Soil conservation is a dominant factor in existing land use policies in the Tahoe basin. These policies can benefit from the incorporation of key soil properties and conditions that influence soil ecology, soil erosion, source/sink nutrient budgets, physical and hydrologic properties, and model use and application. This approach can yield land use policies that have a sound foundation in science.

The profile characteristics and physical and chemical properties of soils are determined by the five factors of soil formation; **parent material**, **biota** (both vegetation and soil biota), **topography**, **climate**, and **time** (Jenny 1980). Primary minerals, or those that come with the soil parent material (e.g., volcanic or granitic origin), are generally unstable when exposed to ambient conditions at the Earth's surface. They begin to disintegrate and dissolve at varying rates according to their resistance to processes of physical and chemical weathering. The soil skeletal fraction consists largely of sand and silts as a result of physical disintegration. On the other hand, ions derived from the dissolution of primary minerals, including essential nutrients such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and many micronutrients, enter the soil solution and either leach to greater depths, become adsorbed to the existing secondary mineral fraction, are taken up by biota, or form more stable secondary minerals themselves. These secondary minerals consist largely of the colloidal (clay) size fractions and contribute substantially to soil chemical properties such as surface reactivity, cation exchange capacity, and anion adsorption (Miller and Gardiner 1998).

Two soil survey reports have been completed for the Tahoe basin; the original published in 1974 (USDA, NRCS, and FS 1974), and a more recent online "Web Soil Survey" published in 2007. The updated version (USDA NRCS 2007) of the soil survey includes some major changes that should be of interest to soil scientists and other specialists studying the Lake Tahoe environment. It presents information on a variety of key soil physicochemical properties, including particle size distribution (texture), structure, percentage clay, organic matter content, permeability, erosion hazard, pH, and cation exchange capacity, as well as delineations of origin (volcanic vs. granitic), flood frequency, frost-free days, mean annual precipitation, and depth to water table.

Soil Physical Properties

Soil texture is determined on the basis of the relative proportions of three general mass size fractions (USDA Classification); the sands (0.05 to 2.00 mm diameter), the silts (0.002 to 0.05 mm diameter), and the soil colloids or clays (<0.002 mm). The larger size fractions (sands and silts) typically settle rapidly and are fairly inert chemically. Soil colloids, however, can remain in suspension over long periods and can directly affect solution equilibrium chemistry as well (see later discussion). Water clarity in Lake Tahoe is largely controlled by absorption and scattering of light by biological and mineral particles that remain suspended within the water column. Of the inorganic fraction, it is the fine particle sizes (1 to 15 μm) that tend to have the greatest effect on lake water clarity because of their tendency to remain suspended within the water column and their light-scattering properties (Jassby et al. 1999, Swift and Perez-Losada 2006).

In terms of soil structure, particles may exist as unattached individual grains (single grain) at one extreme, or become tightly packed into large cohesive blocks (massive) at the other. In between, there exists an intermediate structural condition known as aggregates or peds (Hillel 1998). The interaction between soil texture and soil structure has a pronounced influence on a number of other physical properties such as erodibility, bulk density, porosity, water-holding capacity, and infiltration capacity. These properties in turn have a substantial influence on the soil's ability to support plant growth, the cycling of nutrients, water retention and percolation, and the susceptibility to rill erosion. For example, in addition to being subject to transport mechanisms, nonaggregated or weakly structured soils are more easily compacted upon disturbance (natural or anthropogenic). Compact soils (soils with higher bulk densities) have a lower total porosity and smaller pore sizes skewing the overall pore size distribution throughout the matrix. This typically results in a negative effect by causing lower infiltration rates, which when subjected to high-intensity precipitation, causes greater runoff. It is important to note, however, that for very sandy soils, compaction can also have a positive effect by increasing available water-holding capacity owing to a more compressed pore size distribution.

The process of erosion is of paramount importance to the Lake Tahoe basin. Different soil textures, soil structures, and environmental conditions affect soil erosion. Particulate detachment and transport are the fundamental processes by which erosion takes place. Detachment may be the result of raindrop or particle impact, cycles of freeze/thawing and wetting/drying, overland flow, wind transport,

Courtesy of California Tahoe Conservancy

Bank erosion in a Lake Tahoe basin neighborhood.

or mechanical disturbance. Transport is usually the result of water or wind action with colluviation playing a role on steeper slopes. It is generally thought that increased erosion in upland watershed areas of the Sierra Nevada is largely due to mechanical disturbance from logging, grading, grazing, or other anthropogenic activities that cause loss of vegetation, organic matter, and nutrients from top soil layers; soil compaction; reduced infiltration; and enhanced runoff (Grismer and Hogan 2005a). Several erosion "hot spots" arising from natural and anthropogenic activities exist within the Tahoe basin. Some of the most notable hot spots include upper Ward and Blackwood Creeks, logged areas of the Upper Truckee River watersheds, and areas of high disturbance such as ski resorts and road cuts. Fire aftermath (natural or prescribed) may also result in increased erosion rates (Certini 2005), especially if the burn area is left unattended.

According to the soil erodibility factor (K factor) used for the Universal Soil Loss Equation (USLE), it is the larger sand-sized particles (0.05 to >2.0 mm in diameter) that are the most susceptible to transport because of their size and mass. Smaller size fractions (<0.05 mm in diameter) are less easily mobilized owing to their colloidal nature, but when eroded are more difficult to trap owing to their smaller size.

Soil water repellency (often called hydrophobicity) is a common feature of soils in forested watersheds of the Sierra Nevada that has an effect on soil erosion and soil loss. These effects include reduced infiltration capacity, enhanced overland flow, and increased rainsplash erosion (Shakesby et al. 2000). Naturally derived soil water repellency in the Lake Tahoe area has been reported to be minimal or lacking during moist spring conditions, but most severe during the very dry conditions of late summer (Burcar et al. 1994). Fire-induced water repellency also is of concern. Following wildfire, a hydrophobic layer may exist either at the mineral surface or at some depth below. The depth and thickness of this layer is influenced by the amount of heat, ambient soil moisture content (Shakesby et al. 2000), and particle-size distribution, but does not often exceed 6 to 8 cm (Certini 2005). Whether natural or fire induced, hydrophobicity results in reduced infiltration, enhanced runoff, and, on occasion, mass wasting and deposition.

Recent research indicates that vegetative cover alone (i.e., grasses with 30 to 60 percent cover) may have minimal effects on decreasing erosion from disturbed sites (Grismer and Hogan 2004, 2005a, 2005b). Using woodchips or compost in conjunction with revegetation as a soil restoration method appears to be more effective for providing erosion control, increased infiltration rates, and restoration of hydrologic function (Grismer and Hogan 2005b). The use of compost, however, may also enhance the growth of weeds while decreasing the growth of native vegetation.

Jay Howard

Rain- and hail-induced erosion after the 2002 Gondola wildfire above Stateline, Nevada.

Soil Chemical Properties

Soil chemical properties are directly related to solid particle (organic and inorganic) surface chemistry, geochemistry, fertility, mineralogy, and microbiology/biochemistry. Soil fertility considers soil as a medium for plant growth, mineralogy examines the structure and chemistry of the solid phase, and biogeochemistry studies soil microbial and biochemical reactions (Bohn et al. 2001).

Soil solution is the equilibrium interface between the solid mineral and organic fractions and the atmosphere, biosphere, and hydrosphere. It is the source of mineral nutrients for all terrestrial organisms, and, as it mixes with ground water or drains to streams, lakes, or wetlands, can directly affect their chemistry. The integrating factor of time is also a factor: the importance of parent material to soil properties diminishes over time as the primary minerals disintegrate and are dissolved. Many Sierran soils are relatively young and thus the parent material still has substantial influence over soil properties. For example, soils derived from granitic sources are typically rich in basic cations such as Ca, K, Mg, and Na, whereas volcanically derived andesitic soils are typically more acidic and contain higher concentrations of ferromagnesium minerals (iron [Fe], aluminium [Al], manganese [Mn], Mg). Precipitation strongly affects soil leaching and mineral solubility, temperature affects mineral solubility, and both affect biota, which also has a major influence on soil properties.

Biota has a strong influence on soil properties by adding organic matter, which imparts important chemical properties to soils such as cation exchange capacity and water holding capacity, and nitrogen (N), the most commonly limiting nutrient for plant growth. The organic content of soils is important to a number of soil properties, but especially to aggregate stability, water-holding capacity, plant nutrient supply, and ion exchange. Humus is an intermediate product following considerable decomposition of plant and animal remains (nonhumus). It is amorphous, dark brown in color, insoluble in water, and because of its large specific surface and ability to acquire a positive or negative electrostatic charge in response to soil reaction (pH), exhibits strong ion adsorption and exchange properties. Nitrogen is generally not added with parent materials and their primary mineral components; its source is from the atmosphere, which is 78 percent nitrogen gas (N_2). Unfortunately, N_2 is not available to plants and must first be converted to either ammonium (NH_4) or nitrate (NO_3) forms and added to the soil either naturally through atmospheric deposition or biological N fixation or through the anthropogenic processes of fertilization or air pollution. Nitrogen is therefore unique among nutrients in soil in that it is largely associated with organic matter and has only minimal involvement with secondary minerals or adsorption to colloids.

Fire and fire suppression can have a substantial effect upon various soil chemical properties. A substantial portion of the Lake Tahoe basin is currently considered a high-risk environment for severe wildfire (Murphy et al. 2006b). This is due to a buildup of litter and "ladder" fuels that stimulate a high-intensity ground and crown fire. This shift may be the direct result of fire suppression, resulting in a change in fire regimes from regularly occurring low-intensity fires, characteristic of pre-European settlement, to large often catastrophic stand-replacing fires (Neary et al. 1999).

Fire has a twofold effect on N in the forest ecosystem, and specifically in soils. First, most N contained in material that burns is lost to the atmosphere via volatilization because of its low volatilization temperature. Thus, fire (either wildfire or prescribed fire) causes net losses of N from the terrestrial ecosystem, which, over time, can be important because N is often a growth-limiting nutrient for vegetation. These N losses can be readily restored if N-fixing vegetation, such as snowbrush (*Ceanothus velutinus* Douglas ex Hook.), bitterbrush (*Purshia* sp. DC. ex Poir.), lupine (*Lupinus argenteus* Pursh), and whitethorn (*Ceanothus cordulatus* Kellogg) is allowed to reestablish on the site, thereby providing N input to the system. In the case of shrub species such as snowbrush, however, it may take a decade for such inputs to reach peak values. It is important to note, however, that

N losses from repeated prescribed fire designed to suppress understory vegetation such as snowbrush can equal or exceed those in a wildfire over time, and this may be of concern in terms of long-term forest nutrition.

Secondly, heating of soil and partial combustion of the forest floor normally causes degradation of amino acids and proteins, resulting in an increase (sometimes quite substantial) in soil ammonium levels. This ammonium is basically equivalent to a dose of fertilizer and often contributes to lush growth of herbaceous vegetation after a wildfire. On the other hand, if the ammonium is converted to nitrate during nitrification, surface or ground-water pollution can occur. Wildfire has thus been found to increase the immediate mobilization of labile (readily available) nutrients (Miller et al. 2006, Murphy et al. 2006b). The effect is to increase the frequency and magnitude of elevated nutrient runoff concentrations during the first season following the wildfire event. At least some of this labile N may be transported offsite during precipitation or snowmelt, thus enhancing the nutrient loading of adjacent tributaries (Allendar 2002) and their final discharge into Lake Tahoe. Like N, elevated concentrations of soluble P also may be transported offsite during precipitation or snowmelt ultimately discharging into Lake Tahoe.

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 stream water ammonium and nitrate following a prescribed fire on granitic soils at a western Sierrian site, Stephens 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 at his site was the substantial volatilization of N from forest floor combustion.

Knowledge Gaps

Although a few broad comparative estimates are available (Carroll et al. 2007), historical erosion rates within the Tahoe basin are largely unknown. As a result, we have no means of knowing how current soil loss compares to historical conditions.

This information is recommended to help quantify the extent to which anthropogenic activities have impacted erosion and deposition. The alternative is to directly measure current impacts, but knowledge gaps also exist with this approach. For example:

- The basinwide distribution of developed pervious surfaces such as ski runs, unpaved roads, and gravel parking areas as potential sources of sediment have not been quantified.
- We do not have a quantitative understanding of how developed impervious surfaces (e.g., buildings, roads, or parking lots) have altered natural hydrologic processes leading to increased surface and subsurface discharge runoff and erosion.
- The extent to which jetties, piers, bulkheads, and dredging have altered natural littoral and eolian processes on near-shore soils are unknown.

It remains uncertain as to which erosion control and or site restoration methods are most effective at different locations throughout the Tahoe basin.

- Overall effectiveness in terms of hydrologic function per input effort required is not quantified for most methods at variable site locations.
- How long control measures will remain effective, whether or not they are self-sustaining, and if sustainable, the frequency requirements for maintenance are unknown.
- We do not know how the performance of erosion control methods varies among storm events (e.g., 20-yr vs. 50-yr vs. 100-yr) or changing hydrologic scenarios (e.g., rain-only events vs. rain-on-snow events).

The methods that control the runoff of fine particle sizes most associated with nutrient source/sink loading are not clearly defined.

- Whether or not all “native” soils are a source/sink for N and P remains unknown.
- Quantitative knowledge of equilibrium soil chemistry is recommended to support the proper design of control measures for the reduction of nutrient loading.

The fate and impacts of fertilizer use in the basin are not well understood.

- Fertilizer may or may not be a significant source of nutrients to the lake. The impact of residential fertilizer use is unknown.

How native and nonnative vegetation respond to soil amendments and other restoration activities remains an issue.

- It is unknown whether or not vegetative restoration practices will actually result in the permanent establishment of "native-like" conditions where little natural runoff and erosion takes place.
- Long-term vegetative succession characteristics following the application of soil amendments and other restoration practices are unknown, particularly with respect to whether or not a normal progression of plant community succession can be established, and, if so, how many years may be required for succession.

The presence or absence of vegetation may affect soil shear strengths and aggregate stability, but how and what shear strengths are associated with restored sites is an unknown issue.

- The most effective type of vegetative cover for use at various locations relative to indigenous soil types has not been specified.
- The effects of restoration efforts and vegetative cover on soil aggregate stability are poorly understood.
- What natural aggregate stability is associated with undisturbed sites and what aggregate stability value should be most suitable are not known.

Snowmelt-derived erosion is a poorly understood process and has not been quantified across the basin.

- Most erosion studies have focused on situations and locations such as road cuts, skid trails, and construction, or extreme events.
- Only a few studies (Granger et al. 2001, Riebe et al. 2001) have attempted to characterize baseline erosion from watersheds on an overall basis, including that derived from snowmelt cycles.

The shift from low-intensity fire to catastrophic wildfire has the potential to affect many aspects of soil ecology. Obtaining sound data on the effects of prescribed fire is more practical, but the results may not apply to the effects of wildfire.

- Wildfires have no prefire plan, therefore pretreatment and suitable control sites are rare. Hence, information on the effects of wildfire on organic matter, nutrient cycling, and biological response is scarce.
- Fire suppression has increased organic matter accumulation above and within the soil, and the potential effect on nutrient cycling and discharge to Lake Tahoe is uncertain.

- Information gaps remain concerning postwildfire vegetation recruitment as well as long-term succession and ecological impacts.
- A more comprehensive understanding of pre-European fire regime nutrient cycling conditions would be useful to the development of vegetation management strategies.
- A comprehensive assessment of the effects of both wildfire and prescribed fire and postfire N-fixing vegetation on long-term N budgets is needed.

Little is known about the management implications of soil water repellency in the Lake Tahoe basin.

- The spatial distribution and intensity of soil hydrophobicity has important hydrologic recharge and nutrient "hot spot" implications in Sierran soils (McClain et al. 2003).
- Temporal variability of the effect of soil hydrophobicity on overland flow is unknown, as are individual event-based effects (e.g., how rapidly the effects of soil water repellency dissipate during summer storms or snowmelt cycles remains unknown).
- The role of soil hydrophobicity in soil erosion has not been well studied as it is challenging to isolate the effect of hydrophobicity from those of other erosion factors.
- Most measurements are performed on small-scale areas (<5 to 10 m^2), which yield limited information on spatial variability. These small-scale measurements may not give a reliable indication of the detachment and transport of sediment and nutrients over an entire slope or catchment (Shakesby et al. 2000).

There is a lack of information regarding potential impacts from trace element contamination in the basin.

- Little is known regarding the status of trace elements.
- Fate, behavior, and the related management options are largely unknown.

Research Needs

- Characterize or quantify historical vs. current and natural vs. anthropogenic soil loss on a watershed scale, including intervening zones. Detailed characterization of control site parameters coupled with predictive model estimations would facilitate such efforts.
- Identify the locations, practices, and features that have disrupted the natural littoral and eolian processes sustaining barrier beaches and marshes and influencing beach and dune formation. Where appropriate, develop and evaluate retrofit designs and restoration and management techniques.

- Quantify an aggregate stability index, the hydrologic function, and complete soil nutrient status for soils on native, disturbed, and restored sites. This would provide critical information on the need for restoration and the degree to which we can expect attainment.
- Do a quantitative assessment to determine which restoration methods are most effective in controlling runoff transport of fine particles most associated with nutrient loading and their equilibrium chemistry.
- Evaluate amended or otherwise restored soils in terms of their ability to maintain hydrologic function, productivity, and erosion control over time.
- Identify appropriate vegetation that will best achieve maximum erosion (and potentially nutrient) control at a realistic cost.
- Structure project monitoring and assessment to provide relevant research data pertinent to erosion model development, improvement, calibration, and validation for the Lake Tahoe basin.
- A quantitative assessment of erosion from snowmelt is recommended on different disturbed, native, and restored soils throughout the basin.
- Conduct research on soils and nutrient cycles in natural forests to better understand fire suppression and its role in soil ecology, plant growth, and nutrient discharge. Ideally, sites would be established to measure nutrient cycling, which includes inputs such as plant-soil fluxes through litterfall, crown wash, and root turnover as well as losses from leaching, runoff, wind, or fire.
- Conduct research to understand the effects of wildfire where a suitable adjacent control site is available, especially if prefire data are available (e.g., the Gondola wildfire, Stateline Nevada). Assessment of the immediate and long-term effects of prescribed fire on erosion, hydrophobicity, and runoff rates is recommended, particularly factors that affect the replacement of lost N such as through N-fixation. Ideally, long-term inventory plots would be established to include vegetation and soils to follow the progression of change over time.
- Further quantify the spatial distribution of soil water repellency on a larger scale to determine the distribution of areas of recharge versus those that generate overland flow. Develop a more complete understanding of the factors (i.e., temperature, moisture, vegetation, and litter) that determine the formation, persistence, and dissipation of hydrophobicity to predict seasonal and long-term effects on recharge runoff and erosion.

- Complete, update, and continue refinement of Tahoe basin ecological site descriptions to assist agencies in the development of effective management strategies. An ecological site has specific characteristics that differ from other kinds of land in its ability to produce a distinctive kind and amount of vegetation. Ecological site descriptions include knowledge about site characteristics, plant communities, site interpretations, and other supporting information about such sites and their interrelationships to one another on the landscape.
- Quantify the trace element status of plants, soil, and water in the Tahoe basin.

Development and Application of Predictive Models as Related to Soil Conservation

The Bailey Land Classification System (Bailey 1974) was originally developed to group basin lands into broad classes of similar estimated erosion hazard, then rank each class as to relative environmental sensitivity to land development. It was soon apparent, however, that the Bailey System was inadequate to effectively evaluate the potential erosion hazard for individual parcels. The Individual Parcel Evaluation System (IPES) (TRPA 1986) was therefore developed to provide onsite sensitivity evaluation. Because no site-specific data were readily available, the IPES system used empirical models as the basis for estimating erosion potential. The use of such predictive models when properly applied and interpreted within the constraints of their inherent limitations can provide important tools to understanding and predicting the potential outcome of management strategies and programs. Models related to soil erosion, nutrient cycling, and hydrology can all help to inform actions aimed at soil conservation. The updated version (USDA NRCS 2007) of the soil survey includes a plethora of recent information on key soil physicochemical and biological properties that should be of interest for purposes of model updates to modeling specialists studying the Lake Tahoe environment. Advancing the development and standardized use of predictive models in the Tahoe basin remains a management priority.

Soil Erosion Models

The USLE has been the dominant prediction tool for soil erosion by water for decades. Originally designed to predict sheet and rill erosion on croplands, it has been applied in the United States and abroad for conservation planning to estimate the impact of erosion on the quality of the surrounding landscape (Yoder and Lown 1995).

The USLE equation,

$$A = RKLSCP$$

is based on empirical relationships where A is defined as the soil loss factor, R represents the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover management factor, and P represents the support practices factor (Nearing et al. 1989, Renard et al. 1991, Reyes et al. 2004). The USLE, however, was not designed to predict soil deposition, sediment yield from a watershed (as it does not include deposition), soil loss from single storm events, soil loss from concentrated channel flow in large rills or ephemeral gullies, gully or streambank erosion, or movement of sediment in streams (Hudson 1995; Renard et al. 1991, 1994).

In the mid-1980s, the U.S. Department of Agriculture (USDA) worked to improve USLE by updating and revising the factors involved. This work resulted in the Revised Universal Soil Loss Equation (RUSLE). The RUSLE maintains the same equation structure of USLE, but each feature has been updated using more recent, larger, and more complete data sets (Hudson 1995; Nearing et al. 1989; Renard et al. 1991, 1994; Reyes et al. 2004). At the same time, the Watershed Erosion Prediction Project (WEPP) was being developed in order to produce a more process-based model that would eventually replace RUSLE for upper watershed applications on nonagricultural lands.

Improvements to RUSLE included more data from the Western United States, providing more complete isoerodent maps and thus more accurate R-values for this region. In addition, the R-factor took into account ponding of water on flat slopes where intense rainstorms occurred. Ponded water decreases soil erosion owing to raindrop dispersion, thus the R-factor is decreased. The erodibility nomograph is often used to estimate K-values, but may not be appropriate for all soils. The RUSLE allows users to identify when the nomograph is applicable and when a different method should be applied. The RUSLE also allows K to vary seasonally and accounts for the presence of rock fragments in the soil (Hudson 1995; Renard et al. 1991, 1994). Even so, K-value applicability in the Lake Tahoe basin is questionable. Hence, refining the data input for K-values to make them more pertinent to Lake Tahoe basin conditions would increase the applicability of RUSLE as a predictive tool for the basin.

A major change with the upgrade to RUSLE was the improvement of the L-factor. Choosing a slope length value was originally dependent on the judgment of the user, which resulted in different users choosing different slopes for similar conditions. The RUSLE provides better guidelines that help users to recognize important attributes of field conditions and generate greater consistency when choosing slope length. The slope steepness factor was also revised, and, in most cases, resulted in reduced soil loss predictions (Hudson 1995; Renard et al. 1991, 1994). Of all USLE factors, the P-factor was the least dependable as it represents broad effects of land use practices. Extensive data have been examined to reassess and improve P-factor values for the use of different land use practices (e.g., contouring, terracing, and rangeland practices) for RUSLE application (Hudson 1995; Renard et al. 1991, 1994; Yoder and Lown 1995). Even with these important modifications, however, limitations remain. Like the USLE, RUSLE is unable to predict erosion rates for single storm events or for a single calendar year (Nearing 1989, Yoder and Lown 1995). Furthermore, neither equation estimates deposition or sediment yield at a downstream site or clearly represents fundamental hydrologic and erosion processes (Renard et al. 1991). Ephemeral gully erosion is not included, nor are specific sediment characteristics (Renard et al. 1991).

The WEPP was developed to provide a new technology for modeling erosion for prediction purposes based on what is currently understood about erosion processes. It is a process-based model that offers three versions, each suitable for a different scale. The profile version is the replacement of USLE as a predictor of uniform hillslope erosion, including deposition as an additional component. The watershed version is applicable at the field scale and incorporates areas where more than one profile version applies. The grid version can be applied to areas with boundaries that do not match watershed boundaries, or it can be broken into smaller areas where the profile version may be applied (Flanagan et al. 1995, Hudson 1995, Laflen et al. 1991b).

Major determinants of the erosion process are soil resistance to detachment, stream power (transport), and deposition. Hydrologic processes included in WEPP are climate, infiltration, and a winter component that includes soil frost, snowmelt, and snow accumulation. Plant growth and residue processes estimate plant growth and decay above and belowground. The water balance component uses climate, plant growth, and infiltration to quantify daily potential evapotranspiration, which is necessary to compute water status and percolation. The hydraulic component computes shear forces exerted on soil surfaces. Processes that take place in the soil are also considered, including various soil parameters such as roughness, bulk density, wetting-front suction, hydraulic conductivity, interrill and rill erodibility, and critical shear stress. Tillage, weathering, consolidation, and rainfall impact are also considered (Flanagan et al. 1995, Hudson 1995, Laflen et al. 1991a).

The WEPP, in this respect, is able to estimate spatial and temporal distributions of soil loss, although it has not necessarily provided more precise or realistic estimates of erosion rates. Because the model is process-based, it can extrapolate a broad range of conditions and take into account the variability of topographic conditions of hillslopes (Flanagan et al. 1995). Although process-based models like WEPP may offer more power than an empirical model like the USLE and RUSLE, WEPP requires more complex technology, demanding expanded databases with more advanced computer resources (Renard et al. 1994).

Nutrient Cycling Models

Two models have shown promise for the characterization of nutrient cycling in Sierran systems (Johnson et al. 2000): the Nutrient Cycling Model (NuCM) and the Nutrient Cycling Spread Sheet model (NuCSS).

The NuCM is able to represent the cycling of N, P, K, Ca, Mg, and sulfer (S) on daily, weekly, and monthly time scales at the forest stand level. It also includes the fluxes of major cations (H^+, NH^{4+}, Ca^{2+}, Mg^{2+}, K^+, Na^+), anions (NO^{3-}, SO_4^{2-}, PO_4^{3-}, Cl^-, HCO_3^- , and organic anions), and silicon (Si) in precipitation, soil solution, and throughfall. Throughfall describes the water that falls through the vegetation canopy to the ground surface generating erosive power. The NuCM was designed to simulate the effects of atmospheric deposition, harvesting, change in species composition, precipitation, elevated temperature, and increased carbon dioxide (CO_2). It places heavy emphasis on elements that affect soil solution chemistry, tracking nutrient pools and fluxes associated with soil solution, the ion exchange complex, minerals, and soil organic matter. This model may be most appropriate for determining decadal-scale changes in nutrient pools and soils rather than intra-annual variations in soil solution chemistry (Johnson et al. 2000).

The NuCSS model is a simplified model, but remains more complex than a simple nutrient budget calculation. This model simulates biomass production, organic matter decomposition, N mineralization, cation adsorption, weathering, and leaching. The model estimates a target biomass and associated nutrient uptake using the soil nutrient pools. The user can assess if the available soil nutrients will support the target biomass production (Verburg and Johnson 2001). A key feature of this model is the ease of calibration and, consequently, the simplicity of extrapolation over many sites.

Hydrologic Models

Nutrient fluxes in the Sierra Nevada Mountains are both spatially and temporally variable (Johnson et al. 2001), and a better means of predicting changes in the amount of biologically available nutrients discharged from upper watersheds is needed. The ability to better assess what is occurring spatially in terms of surface runoff alone could offer a linkage in balancing the overall nutrient budget for eastern Sierra Nevada watersheds. One approach is to develop a methodology for delineating a spatially explicit water balance that adequately estimates the potential for surface runoff over large areas using available input/output spatial data (Carroll 2006).

Most recent hydrologic applications involve some use of geographic information systems (GIS) for the ease of estimating model parameters. For example, GIS has been used to estimate and organize important hydrologic modeling parameters such as soil type, land use, slope, flow direction, elevation, drainage network, rainfall, evapotranspiration, and vegetation (Alemaw and Chaoka 2003, Bourletsikas et al. 2006, Jain and Singh 2005, Jain et al. 2004, Schumann et al. 2000). It can also be taken a step further: Liu et al. (2003) applied GIS to better estimate complex parameters requiring multiple spatial inputs such as a potential runoff coefficient as determined from slope, soil type and land use, and flow velocity and dispersion as determined from slope, hydraulic radius, and vegetation coverage. Much of this information may be found in the 2006 soil survey for the basin (USDA NRCS 2007).

Once data have been compiled, there are many variations on how they could be applied to hydrologic modeling. Fluvial transport of sediments occurs when water velocities are strong enough to overcome shear strength of the soil, transporting sediment downstream. Fine particles are often transported as suspended load, moving downstream while suspended in the water. Sufficiently larger particles may be transported as bedload, settling on the river or streambed, but still moving downstream. Areas that lack vegetation because of wildfire or other anthropogenic factors are more susceptible to water erosion and consequent downstream transport. Surface waters often transport these soils to a lower land area or receiving water body, such as Lake Tahoe. If possible, such a model would help researchers to more fully understand the magnitude and sources of nutrients and sediments that are being transported into tributaries and surrounding reservoirs and lakes (Carroll 2006).

Knowledge Gaps

Different agencies in the Lake Tahoe basin use different methods to predict soil erosion and to assess the need for erosion control measures.

- The issue remains whether any of the erosion models and equations is adequate for use in the Tahoe basin. The USLE was originally developed to predict erosion rates on agricultural lands with relatively mild slopes, thus its applicability for the basin is questionable. The RUSLE may compensate for some deficiencies of USLE but may still be inadequate.

- Although WEPP may be the most inclusive model by incorporating a climate and soil database, it is by far the most complex. There needs to be consistency among agencies as to model use and application.
- In the event that the current models are not adequate predictors of soil erosion for the Tahoe basin, appropriate modifications or adjustments are needed to make the existing models more functional. If this is not an option, starting from scratch and developing a new model that is simple, accurate, and appropriate for the basin may be necessary.

There is a particular need for generating refined erosion estimates for single-storm episodes as compared to seasonally weighted or seasonally adjusted annual erosion loads for purposes of programmatic modeling, BMP interpretive assessment, and design criteria. This is particularly true in the Lake Tahoe basin, where there is large variability among storm systems, and single events can result in major runoff.

- Modeling single-storm episodes would be useful for planning and modeling applications, especially for BMP design and implementation associated with new development or redevelopment.

From a management perspective, there is a lack of information on the effects of sediment transport and delivery, pertinent soil parameters, the effects of diminished impervious cover, fire effects (wildfire and prescribed), and the effects of fuel reduction on soil erosion. Information is also lacking on the need for specific erosion control practices.

- Hydrophobic soil conditions have been shown to increase a soil's vulnerability to erosion by increasing aggregate instability, reducing infiltration, and increasing overland flow (Robichaud 2000, Shakesby et al. 2000). Management options to deal with these vulnerabilities have not been defined.
- The increased potential for soil erosion following fuel reduction activities, as well as site susceptibility and response to a subsequent catastrophic event, has not been quantified.
- Fire suppression efforts, recreational development such as ski resorts, and recreational activities such as mountain biking or off-highway vehicle use, can all exacerbate soil erosion as well as soil compaction (Backer et al. 2004). The significance of these anthropogenic activities is not well understood, especially with respect to erosion modeling and their importance as input parameters.

There is no hydrologic model specific to the needs of the Tahoe basin.

- A spatially explicit water balance model, specific to the needs of Sierran forested watersheds, is clearly needed to more fully understand nutrient and sediment transport.
- Furthermore, there are several unusual factors that can affect surface water modeling and model output in the basin such as the spatial distribution of hydrophobicity, frequency and presence of frozen soils, and frequency and intensity of rain-on-snow events that are not addressed in most models currently in use.

Erosion, nutrient cycling, and hydrologic models have yet to be tested against the effects of fire and fuel reduction.

- The effect of fire suppression, wildfire, and prescribed fire for fuel reduction is currently being studied to some extent, but the potential effects of impending climate change are a major unknown.

Research Needs

- Evaluate the accuracy and application of models on a site-specific basis, to determine if the models currently in use are adequate in predicting soil erosion and sediment delivery within the Tahoe basin.
- Determine the role and impacts on soil erosion of hydrophobic soils, fire and fire suppression efforts, and the effect of recreational activities.
- Gain a better understanding of flow patterns, fine and coarse sediment loading, deposition, erodibility, infiltration, slope, and hydrophobicity.
- Establish improved engineering guidelines, predictive tools, and cost-effective management approaches for the control of nutrient and sediment transport from upper watersheds and other high-impact areas of the Tahoe basin.
- Develop site-specific parameterization and model calibration. A prioritization is recommended of which soil parameters are important, what should be measured, and what information is needed to parameterize and calibrate the models.
- Make models more applicable to the basin by improving data input whenever possible, such as the K-factor in USLE and RUSLE equations.
- Understand and quantify the effects of fuels reduction activities on soil conservation. This necessitates recharacterization of infiltration, runoff, nutrient cycling, erosion, and general growing conditions for revegetation at the watershed and subwatershed scales.

- Conduct quantitative evaluation and assessment of potential soil loss from hillsides and sediment trapping within stream environment zones as a result of catastrophic events such as wildfire, rain-on-snow, and excessive rainfall events.
- Develop a spatially explicit water balance model, specific to the needs of Sierran forested watersheds, to more fully understand sediment and nutrient transport, the goal of which is to better assess the linkage between overland flow sediment and nutrient transport and discharge water quality. Applying the appropriate water balance information, localized point source surface runoff and nutrient data could then be used to quantify discharge loads at the watershed scale.

Effects of Climate Change as Related to Soil Conservation

Global climate change is in part the result of greenhouse gases accumulating in the atmosphere. Predictions for the next century include a 3-°C rise in global temperatures (Roos 2005). Warmer temperatures would increase global evaporation and therefore increase global precipitation, much of which is predicted to occur in northern latitudes (Roos 2005).

Depending on the models that are used, predictions for precipitation quantity and intensity are quite variable for the Sierra Nevada. In some predictions, precipitation events will increase in intensity leading to large-scale flooding. In other models, the Lake Tahoe area will be subject to warmer temperatures and more evapotranspiration, and increased precipitation will be more common farther to the north outside the basin. One analysis using General Circulation Models found Lake Tahoe to be one of the few areas where precipitation quantities remained about the same, even with a doubling of CO_2 in the atmosphere (Phillips et al. 1993).

There is general agreement, however, that with warmer temperatures, snow elevation levels will be higher. The Lake Tahoe basin has elevations ranging from roughly 1885 to 3070 m. Snow levels in the area typically range from 1520 to 2432 m during the winter months. It is estimated that for every 1-°C rise in air temperature, the snow level will rise approximately 152 m (Roos 2005). As the basin sits right in the range of the average snow level, a rising snow level means less snowpack for the Lake Tahoe region. More rain and less snow throughout the winter will have important effects on watershed and regional hydrology. Soil quality and soil erosion are the two areas pertinent to soil conservation that will be affected by climate change and its effects on weather patterns and hydrology.

Soil Quality

Snowpack in alpine areas can greatly influence microbial communities. A thick layer of snow acts as insulation to subsurface biota, keeping temperatures hovering around freezing instead of fluctuating with the air temperature to well below freezing (Nemergut et al. 2005). A thin snowpack or none at all leaves these communities vulnerable to the sometimes harsh Tahoe climate. During the winter months, these microbial communities are responsible for a large portion of the plant matter decomposition, thereby mineralizing and immobilizing N (Nemergut et al. 2005). Harsh weather diminishes their numbers and therefore the amount of decomposition that occurs. Slowed decomposition rates lead to fewer nutrients available for uptake the following year. Longer growing seasons will also lead to increased nutrient demand by vegetation, not only of N but carbon as well (Euskirchen et al. 2006). Ultimately, a diminished or more variable snowpack could lead to large duff layers and nutrient-deprived soils.

Soil Erosion

The main issue to confront when discussing soil erosion and climate change in the Lake Tahoe basin is the shift from large snowfall events to large rainfall events. The Lake Tahoe basin receives an average of 10.7 m of snow annually with an average of 3.2 m of annual snow at lake level. However, analysis presented in the "Water Quality" chapter found that the fraction of precipitation that falls as snow rather than rain is decreasing.

Current regulations require drainage structures and erosion control mechanisms to be able to withstand a 20-year storm, or a storm producing 2.54 cm of rainfall in 1 hour. If more winter precipitation is received as rainfall rather than snow, current structures may not be able to withstand the strain. Large rainfall events could erode slopes and flood drainage control structures allowing surface water laden with sediments and nutrients to discharge directly into Lake Tahoe. More rain during the winter also increases the possibility of rain-on-snow events. Recent history, such as the flood of 1997, has shown how catastrophic a large rain-on-snow event can be.

Another issue with variable rainfall is its effect on soil moisture. Rapid melting of a smaller snowpack would lead to a decrease in soil moisture during summer months owing to an earlier runoff. Sarah (2005) reported that less rainfall and therefore less soil moisture is associated with an increase in microparticle percentage and a decrease in aggregate stability. Hence, a decrease in snowpack could ultimately lead to increased instability of slopes and a higher incidence of erosion in the Lake Tahoe basin. Better characterization of amount, rate, duration, and seasonal occurrence of rainfall precipitation could help to delineate shifts in the local climatic precipitation phase and the potential impact on erosion, model estimations, and BMP design criteria.

Knowledge Gaps

How soil biota is affected by a decrease in snowpack as a result of climate change and the consequent result on soil nutrient content is uncertain.

- There is limited information about how climate change will affect microbial communities in the soil, their health, and their functionality.
- There is limited understanding of how climate change will affect the breakdown of plant material.
- Research is recommended to determine if soil nutrient contents will ultimately be affected by microbial community health and increased plant matter production.

How a change in frequency and intensity of rainfall will affect erosion rates is unknown, specifically excessive rainfall and rain-on-snow events.

- We do not understand how episodic events, such as flash floods, will affect Total Maximum Daily Loads (TMDLs) in Lake Tahoe. The ability to predict the recovery time from these natural disasters as well as anthropogenic disasters could benefit many agencies.
- We do not know the relationship between increased intensity and frequency of precipitation events and the resulting erosion rates.

A tool/data set is recommended to modify precipitation data used in sediment loading models to predict the effects of climate change. How this can be used to determine TMDL and the effect of different storm events has yet to be determined.

- Several models are available, many predicting different futures for the Lake Tahoe basin. If model results contain uncertainty, then this uncertainty should be quantified and accounted for as part of the input to subsequent models.
- We are not certain what will happen with climate change: therefore it is extremely difficult to plan for the future of the Tahoe basin. Development and evaluation of alternative scenarios is one objective approach that could help to inform managers of the future possibilities.
- Current regulations only require new drainage control and erosion mechanisms to be capable of handling a 20-year storm event. What happens with a 50-year storm? What happens if there is frequent repetition of 20-year storm events?

How soil stability is affected by climate change is unknown.

- If soil moisture decreases during summer months owing to decreased supply from accelerated winter snowmelt, there could be a resultant decrease in soil aggregate stability.
- If soil moisture increases owing to increased precipitation events throughout the year, soil aggregate stability could increase, but we could see an increase in surface soil removal or an overall decrease in slope stability.

Research Needs

- Study microbial communities and their relationship to climate change and soil nutrient flux in the Lake Tahoe basin. Determine their niche and if climate change will remove certain species from the Tahoe region. This information would include a better understanding of their temperature range, soil moisture requirements, and tolerance to frozen soils. All of this ultimately would concentrate on understanding the effects microbial community health has on soil nutrient cycling.
- Explore the relationship between possible intense summer and winter rainfall storms and erosion rates. Ideally, this research also would look into the rate of snowmelt during rain-on-snow events and the resultant erosion. Do frozen soils help to protect soil surfaces from erosion or increase erosion of surface layers?
- Examine the ability of stormwater management practices such as BMPs, drainage control, and erosion control to diminish sediment and nutrient transport to Lake Tahoe. Do structures designed for a 20-year storm function to their intended design? Do these structures remain functional but at a diminished capacity during a 50-year storm, or do they fail entirely? Future designs could be developed to account for the possibilities that global climate change brings.
- Run all models for the wide range of possible changes in precipitation that may accompany global climate change. New models such as the Channel Change GIS Simulation Model (CHANGISM) described by Hooke et al. (2005) can be used to determine the effect of global climate change on stream environment zones (SEZs) and the implications on nutrient and sediment loading into Lake Tahoe.
- Test the implications of climate change on soil stability. Aggregate stability, surface soil stability, and overall slope stability would all be tested with different possible moisture regimes to determine what the ultimate effects of global climate change could be on soil erosion potential. In addition,

quantifying the sources of sediment would be useful for identifying and initiating management strategies at the most serious locations.

- Explore future ecosystem scenarios. There is concern that long-term restoration may not be possible owing to the emergence of heretofore nontypical ecosystems.

Policy Implementation and Adaptive Management Strategies as Related to Soil Conservation

Public input into the management and conservation of Lake Tahoe basin resources has taken many forms since decline in Lake Tahoe water clarity became a broadly recognized environmental concern. Surveys have been conducted regarding the public knowledge base on environmental issues, and regular news releases and reports have been issued to further educate the public on BMPs and other environmental issues in their community.

Lake Tahoe also has been a longstanding subject of interest for researchers. Educational and research institutions such as the University of Nevada, Reno, the University of California, Berkeley, the University of California, Davis and the Tahoe Environmental Research Center (TERC), the Pacific Southwest Research Station, the U.S. Geological Survey, and the Desert Research Institute all have contributed time, money, and effort to monitoring and studying many aspects of the lake and surrounding watersheds.

The Lake Tahoe Interagency Monitoring Program (LTIMP), a longstanding cooperative program created to acquire and distribute water quality information, has been collecting data on Lake Tahoe and its watershed since 1980. Many federal, state, and local agencies, as well as several nongovernmental agencies are active entities whose interests are directed toward protecting Lake Tahoe water quality by promoting preservation, restoration, sustainability, and environmentally sound development.

The balance of Lake Tahoe's ecosystem is delicate. Excellent communication among the scientific community, the public, and policymakers is recommended for Lake Tahoe to benefit from all of the efforts that go into protecting this precious resource. One aspect of adaptive management is the integration of current research into policy and management decisions and implementation. Current regulations in the Lake Tahoe basin regarding soil conservation, including BMPs to control erosion and sediment transport, protection of sensitive areas such as steep slopes and SEZ, and the mitigation of impervious coverage, can all benefit from a basinwide adaptive management framework.

Resource and regulatory agencies—
The monitoring of water quality management projects has been listed as a primary function of the Lahontan Regional Water Quality Control Board (LRWQCB). The Nevada Division of Environmental Protection (NDEP) and its water quality subsidiaries also oversee water quality issues on the Nevada portion of the basin (NDEP 2007). Both the LRWQCB and the NDEP are leading the effort to develop TMDL pollution budgets for Lake Tahoe. However, both of these state agencies rely heavily on the ordinances set forth by the Tahoe Regional Planning Agency (TRPA) to enhance water quality in the Tahoe basin.

The TRPA oversees much of the implementation and regulation of the water quality planning in the Lake Tahoe basin. Their established “Goals and Policies” call for application of land capability ratings in the planning for new construction and the authorization of additional impervious cover. Likewise, the “Code of Ordinances” ensures SEZ habitat is protected, and the repair of damaged SEZ habitat is authorized. Furthermore, chapter 25 of the TRPA Code of Ordinances calls for the BMP Retrofit Program, in which private and commercial landowners must install stormwater and erosion control BMPs with a capacity to assimilate the stormwater runoff from a 20-year storm event.

The U.S. Forest Service Lake Tahoe Basin Management Unit (LTBMU) manages soil conservation and water quality preservation on Forest Service lands. Monitoring is conducted on many LTBMU projects. The LTBMU has several monitoring programs such as the BMPs evaluation program, fuel reduction project soil monitoring, road decommissioning and BMP-upgrade program monitoring, trail decommissioning and BMP-upgrade monitoring, off-highway vehicle program monitoring, and urban erosion control grant program monitoring (USDA FS 2005). Results from monitoring projects are compiled and reported anually. The 2006/2007 Annual Monitoring Report was recently completed. This report presents a summary of data collected in calendar year 2006, as well as results of analysis conducted fall 2006 through spring 2007. The report contains much information regarding efforts related to monitoring of fuel reduction program, soil and water BMPs, restoration projects, and status and trend of biological resources. It is anticipated that the 2007/2008 Annual Monitoring Report will be completed on schedule, by late summer 2008. The findings identified in these reports have been used to make decisions in terms of which practices will be continued and what modifications in implementation or construction may be necessary. These Annual Progress Reports published by the U.S. Forest Service can be accessed by the general public through the following link, http://www.fs.fed.us/r5/ltbmu/ by clicking on the publications tab and then scrolling to LTBMU Monitoring Reports.

The U.S. Geological Survey (USGS) is another federal agency involved in the management of the Lake Tahoe basin. The USGS has provided numerous resources to help understand and conserve the basin's ecosystems, and, among other things, they provide various geographic and cartographic data useful to resource managers. Such resources include a bathymetry map, a digital elevation model, a digital orthophoto quadrangle, a digital line graph, a digital raster graphic, numerous satellite images, a digital soil map, and a digital census map. The USGS is also one of the principal partners in the LTIMP stream monitoring program.

The California Tahoe Conservancy (CTC) is a state agency developed to create and implement programs that improve and protect the environmental quality of the Lake Tahoe basin. Protection of the clarity and quality of the lake's waters is a primary objective of CTC. Additional goals and programs are geared toward the preservation and protection of wildlife and wildlife habitat, environmentally sensitive land, SEZ habitat, forest habitats, and recreation opportunities (CTC 2006). The CTC is only active in the California portion of the basin.

The Natural Resource Conservation Service (NRCS) is an agency within the USDA that provides data, information, and technical expertise on natural resources. Their primary customers are those who manage and use natural resources on nonfederal lands including farmers, private organizations, and non-profit organizations (USDA NRCS 2007). An important recent contribution has been the 2006 update of the Soil Survey of the Tahoe Basin Area (USDA NRCS 2007).

The Nevada Tahoe Conservation District (NTCD) is a subdivision of the state of Nevada whose mission is to "promote the conservation and improvement of the lake Tahoe basin's natural resources by providing leadership, education, and technical assistance to all basin users" (NTCD 2003). The NTCD is active in the Nevada portion of the basin and is involved in a number of projects including erosion control, water quality, the Backyard Conservation Program, and a stormwater planning initiative.

The Tahoe Resource Conservation District (TRCD) is a conservation district for the state of California that is active on the California side of the basin. Programs within TRCD include the Backyard Conservation Program, an invasive weeds program, a schoolyard restoration program, a watershed program, and most recently an aquatic invasive species program. The TRCD works in close cooperation with the NTCD (TRCD 2007).

Best Management Practices

Best management practices have been developed to minimize wind and water erosion, uncontrolled surface runoff from urban areas, and ultimately sedimentation and nutrient loading into Lake Tahoe. Urban runoff is considered a greater source of sediment and nutrients than undisturbed areas and is therefore of primary concern (LRWQCB and NDEP 2008a, 2008b, 2008c; Schuster and Grismer 2004; TRPA 2001a, 2001b). In 1992, the TRPA implemented the BMP retrofit program requiring all property owners to upgrade their property with BMP technology. Best management practices can be divided into three categories: temporary construction, permanent drainage control, and permanent surface stabilization.

Temporary construction BMPs deal with the exposure and disturbance of soils and vegetation on a construction site. They are therefore temporary solutions designed to minimize the impacts of the immediate disturbance activities. Often included are temporary structures to stabilize and protect areas such as boundary fencing to protect environmentally sensitive areas from encroachment: fiber roll barriers, filter fences, drop inlet barriers, and gravel bags all of which act as sediment barriers; and erosion control blankets, mulches, and tackifiers to maintain unstable slopes (TRPA 1988). Construction sites also participate in activities such as traffic control where traffic is kept to areas that will have the same use postconstruction, stabilization of construction entrances to minimize transport of sediments outside of the construction zone by vehicle traffic, and dust control by maintaining surface cover by moistening, vegetating, or mulching exposed surfaces (TRPA 1988, White and Franks 1978). Construction sites disturbing more than 1 acre of soil are required to file a Storm Water Pollution Protection Plan (SWPPP) as mandated by the National Pollutant Discharge Elimination System (NPDES) under the Clean Water Act (NDOT 2006, SWRCB 1999). The SWPPP specifies which BMPs will be applied to prevent all construction pollutants and erosion products from entering stormwater and exiting the construction site (SWRCB 1999). It also is required that this plan detail maintenance procedures and self-inspections that will be conducted to ensure the optimum performance of applied BMPs (NDOT 2006). The filing of the SWPPP is implemented and enforced by the LRWQCB and the NDEP.

Permanent drainage control is used to minimize the effects of impervious areas and diminish the capacity of surface runoff carrying nutrients and sediments to move offsite. The continual growth of impervious area such as rooftops, driveways, compacted soils, patios, and decks is a side effect of urbanization. Numerous BMPs have been designed to address the problems associated with large areas of reduced or zero infiltration and the production of large quantities of surface runoff. The first step is the installation of conveyance systems, such as slotted drains, swales, subsurface drains, gutters, downspouts, deflectors, gravel trenches, or gravel armor, which all intercept runoff perpendicular to the direction of flow and then divert it to an infiltration system (TRPA 1988). Next is the installation of surface infiltration systems such as naturally flat vegetated areas, infiltration trenches, drywells, gravel armoring layers, retaining ponds, and planter boxes (TRPA 1988). These systems retain water, allowing sediment to settle and the water to infiltrate into the soil, which has inherent cleansing abilities for some nutrient components.

Permanent surface stabilization is designed to reduce the impacts of unstable, steep, or exposed soil surfaces. Compacted soils that do not infiltrate can be paved to avoid erosion or vegetated to improve infiltration (TRPA 1988). Vegetation also can be used to stabilize slopes. Other methods of slope stabilization include willow wattling, terraces, retaining walls, mulching, and erosion control blankets (TRPA 1988). Which method(s) are most appropriate depends largely on the steepness of the slope.

One of the most recent soil conservation issues is the defensible space program and the need for BMP implementation within the 0- to 30.5-m range by private homeowners. Guidelines are currently being developed for any person who owns, leases, controls, operates, or maintains a building or structure adjoining any mountainous area, forest-covered lands, brush-covered lands, grass-covered lands, or any land that is covered with flammable material. Such a defensible space perimeter would provide firefighters a working environment helping them to protect buildings and structures from encroaching wildfires as well as minimizing the chance that a structural fire would escape to the surrounding wildland. A key concern is the development of appropriate management strategies that maximize defensible space but at the same time function to minimize erosion and the degradation of runoff water quality.

BMP Effectiveness

To some extent, most BMPs are effectively reducing erosion and thereby reducing total sedimentation and nutrient loading to the lake. A study was conducted from 1974 to 1977 comparing sediment yields from two development sites in or near the Tahoe basin: Northstar-at-Tahoe and Rubicon Properties Unit Number Two. Construction of one site (Northstar-at-Tahoe) included erosion control methods and the other (Rubicon Properties) did not. Sediment yield from Northstar-at-Tahoe increased by about 100 percent above the very low background levels associated with predevelopment conditions, whereas sediment yield from the Rubicon Properties site was found to be approximately 10,600 percent above background levels well after development (White and Franks 1978). Evaluation of the sample plot at Rubicon Properties led researchers to believe that implementation of erosion control methods similar to those at Northstar-at-Tahoe would help reduce sediment yields to approximately 100 percent above background levels at Rubicon; however, data to this effect could not be found.

Identification as to which BMPs are most effective and to what degree for any given scenario is therefore important. Best management practice effectiveness is a function of three factors: design, construction, and maintenance. Choosing the most effective BMP requires sufficient knowledge of BMPs and their applicability depending on location and other site-specific conditions within the basin. Cost effectiveness is an additional issue to be considered when choosing the most appropriate BMP. A BMP that is the most effective in reducing sediment yield may not be cost effective owing to site conditions, materials, or labor requirements; hence, it may not be practically feasible. Alternatively, a BMP might be both cost and functionally effective in reducing sediment yield, but require excessive maintenance reducing its viability as a long-term method of erosion control. It is essential that each aspect be considered when selecting the most appropriate BMP. The question of which BMPs are most effective is best determined by having a full “toolbox” of BMPs from which to choose, and then having the knowledge and experience to apply the correct BMP to match onsite situations.

Although it is considered best to minimize disruption and keep native vegetation intact whenever possible (Gray et al. 1980, Lynard et al. 1980, TRPA 1988), this is seldom feasible during construction activities. In such construction zones, revegetation and gravel mulches have been shown to be an effective means of erosion control on disturbed, bare soils. On the other hand, simple sprinkling has been found to be an inefficient practice (TRPA 1988). It requires large amounts of water, needs several applications daily, and creates sediment-laden water. In terms of sediment traps, straw bales do not trap much sediment and create a noxious weed hazard, and sandbags can tear and add additional sediment to flow (TRPA 1988). Fiber rolls and filter fences can be efficient sediment traps when installed correctly but unfortunately they seldom are (TRPA 1988). Therefore, temporary construction BMPs run the risk of frequently being ineffectual and require great vigilance on the part of authorities to make sure that they are being implemented and maintained correctly.

For permanent drainage control, conveyance systems are used to direct surface runoff to a point of infiltration within the property line. Infiltration effectiveness is assumed but is unknown. Slotted drains are most effective for conveyance on driveways, but are quite costly, and swales cannot be installed on slopes greater than

5 percent (TRPA 1988). Berm construction is no longer a recommended practice because they lose functionality over time owing to the harsh Tahoe climate. The most appropriate infiltration systems for use are often determined by soil characteristics such as bulk density, water-holding capacity, hydraulic conductivity, and soil water repellency. Vegetation is often used to enhance the efficiency of certain drainage structures such as swales or channels by reducing flow velocities and thereby allowing time for greater infiltration. Gravel and other infiltration trenches are typically inappropriate structures on slopes, and gravel armor is only effective when used on highly permeable soils (TRPA 1988).

The use of native vegetation has always been considered an effective means of retaining surface stabilization (Lynard et al. 1980). Once soil is bared, however, the combination of vegetation and mulch has been proven an effective method of stabilizing it (Grismer and Hogan 2005a, 2005b). Erosion control blankets, seeding and fertilizing, and wood fiber coating have all been found to be effective slope stabilizers; however, seeding alone was highly ineffectual (Leiser et al. 1978). Establishing vegetation on a steep slope can be quite difficult. It has been noted that high vegetation mortality can be the result of unstable slopes (Leiser et al. 1978). In this case, it is generally recommended that vegetation efforts can be supported with some kind of slope stabilization (Lynard et al. 1980). A combination of wattling and willow cuttings were found to decrease sediment yields from a road cut from approximately 83 m^3/yr to almost nothing (Leiser et al. 1978). In fact, in a 1978 U.S. Environmental Protection Agency report it was noted that contour wattling should be applied more often (White and Franks 1978).

BMP Maintenance

Different erosion control structures require different levels of maintenance to remain effective, although regular maintenance is often important. For example, regular cleaning of conveyance structures is necessary to remove accumulated debris (TRPA 1988), and infiltration systems require regular cleaning to maintain maximum storage capacity. Although no clear maintenance schedule is given for conveyance and infiltration structures, it is recommended that they be examined after each storm to determine if cleaning is necessary. Organic mulches are best replaced yearly owing to decomposition loss. Mortality loss of vegetation coverage is best compensated for with the establishment of new vegetation (TRPA 1988). Vigilance is a major aspect to the maintenance of effective BMP structures. This is highly dependent on the level of devotion, regardless of whether the application is at the jurisdictional, the individual property owner, or the responsible regulatory agency scale.

Stream Environment Zones

Stream environment zones are wetland, flood-plain, and riparian areas that influence the surface water quality in the Lake Tahoe basin. They have traditionally been considered an important means of reducing nutrient and sediment loads and surface water velocity before discharge into Lake Tahoe. In 1982, the TRPA stipulated that SEZ habitat should be protected in its natural state, that all disturbed SEZs in undeveloped areas would be restored, and that at least 25 percent of the disturbed SEZs in developed areas would be restored (TRPA 2001a, 2001b). From 1980 to 1986, 61 ha of SEZ were restored; 28 ha were restored from 1987 to 1991; 41 ha were restored from 1992 to 1995; and 62 ha were restored from 1996 to 2001. In order to attain its SEZ habitat threshold, TRPA (2001a, 2001b) set a goal of restoring 253 ha of SEZ habitat by 2006, of which 148 ha of SEZ were restored (TRPA 2006a, 2006b) by that date. Threshold attainment is reevaluated every 5 years.

Impervious Coverage

Impervious coverage is land that is unable to infiltrate surface water owing to paving, soil compaction, or structural coverage. Impervious coverage leads to increased surface water runoff, thereby increasing flow velocities, erosion potential, and sediment transport, as well as the production of other pollutants such as vehicle oil and grease, tire dust, and hydrocarbons from pavement. In 1982, the TRPA adopted the threshold policy that impervious coverage will comply with the land capability classification system set forth for the Lake Tahoe basin by Bailey in 1974 (TRPA 2001a, 2001b). This land capability classification determined how much impervious coverage an area can handle based on its perceived hydrologic characteristics and is currently applied to all parcels developed before 1987. Bailey classifications were originally determined from soil and hydrologic features characterized by the original Tahoe basin soil survey report (USDA SCS and FS 1974), but may require revision based on the now updated soil survey (USDA NRCS 2007) to remain consistent. In 1987, the TRPA implemented the Individual Parcel Evaluation System (IPES) as its method for determining allowable impervious coverage on vacant or undeveloped lots. A numerical value is assigned to each parcel, which is calculated from its relative erosion hazard, runoff potential, degree of difficulty to access the building site, SEZ, condition of the watershed, ability to revegetate, need for water quality improvements in the parcel vicinity, and proximity to Lake Tahoe. The IPES field evaluation team determines the parcels most eligible for development (those with the highest IPES score) and ranks them accordingly for each jurisdiction.

The Tahoe Environmental Geographic Information System (TEGIS) was developed in 1987 to track the amount of impervious coverage. Research with the Desert Research Institute and TRPA has proved effective in being able to use satellite imagery and aerial photography to improve this database. However, it was not detailed enough to be applied in the 2001 TRPA monitoring of threshold attainment. Instead, project reviews, compliance records, and files were used to establish comparisons for the levels of new and old impervious coverage. From this it was determined that as of 2001, the Tahoe basin was not yet in attainment with the land capability threshold. Furthermore, it was believed that attainment could not be achieved by 2006. To our knowledge, no set schedule for attainment has been established (TRPA 2001b).

Although attainment of the impervious coverage threshold has yet to be met, there is some evidence that the IPES program may be helping to reduce sediment loads discharging into Lake Tahoe. A study conducted by the Desert Research Institute in 1999 reported that 9 of 10 Lake Tahoe tributaries have seen a decrease in suspended sediments since the implementation of the IPES program in 1989 (TRPA 2001b). This study has yet to be published in a peer-reviewed journal, and it is currently unknown whether or not the relationship was coincidental. Without detailed information, it is difficult to determine if the reduction in suspended sediments was actually related to the IPES program, or the result of other management strategies, climatic variation, or a combination of related factors.

Implementation and Regulation

Despite TRPA's efforts in regulatory management for water quality protection, our experience in the Tahoe basin suggests there is a serious lack of community participation and understanding as to the importance of monitoring for BMP effectiveness and the relationship between impervious cover restrictions and SEZ protection that are pertinent to soil conservation (i.e., the reduction of nutrient and sediment loading) and the enhancement of stream and lake water quality. Although the monitoring of water quality management projects has been listed as a primary function of the LRWQCB, such evaluations have been difficult to conduct, and there does not appear to be much available to the general public regarding the efficiency of programs that have been implemented. As of June of 2006, an estimated 36,000 properties of the approximately 42,000 developed parcels in the Tahoe basin remained in noncompliance (Fehd 2006). With a reported rate of 150 to 175 free evaluations available per month (Fehd 2006), and the limited construction season (May–October), it appears unlikely that this goal will be reached. The public might be more active in their participation if the required BMPs could be quantitatively demonstrated as the most effective of the BMP tools and, if applied, how much their individual involvement could directly improve water quality.

Although there are gaps in monitoring and reporting of water quality protection efforts in the Lake Tahoe basin, there have been some successes as well. The LTBMU actively monitors management practices, facilitates the implementation of new research into policy, and actively participates in the dissemination of research results. The Annual Progress Report published by the USDA Forest Service, as well as the individual reports compiled for each monitoring project, allow interested members of the public the opportunity to educate themselves on topics concerning the preservation of Lake Tahoe's water quality and surrounding soils. The use of monitoring results in decision and policymaking are fundamental to the success of adaptive management.

Regional Planning

Regional planning has been enhanced by the Environmental Improvement Program (EIP). The EIP was established in concert with the 1997 Lake Tahoe Presidential Forum. It outlined a 10-year plan investing $980 million into the Tahoe basin (TRPA 2006b). These investments have aided soil conservation efforts through the acquisition of sensitive lands, restoration of sensitive areas, treatment and removal of unpaved roadways in forested areas, funding of monitoring assessment programs, and the establishment of and technical assistance to EIP partners. For example, the new NRCS Soil Survey is counted as a federal contribution of technical assistance under the EIP. The list of EIP partners is extensive and includes almost all research, governing, and public institutions involved in maintaining Lake Tahoe basin environmental integrity (TRPA 2001b).

The 20-year regional plan guiding TRPA programs expired at the end of 2006. It was subsequently determined that the public was very confused on environmental issues, that they lacked understanding of regulatory policy, and they did not grasp how their individual actions could have substantial impacts on the fragile Lake Tahoe ecosystem (Pathway 2006, 2007). Consequently, it is extremely important that members of all components of the community are involved in the development of a new regional plan.

Knowledge Gaps

Regulatory compliance and the effectiveness of management strategies on privately owned portions of the Lake Tahoe basin are unknown.

- Government agency monitoring of the effectiveness of their programs is inconsistent and does not make public the results or findings of fact.
- Because there is a lack of understanding as to the relationship between BMP effectiveness and the enhancement of stream and lake water quality,

Tahoe residents are not always predisposed to comply with existing regulations.

- The agencies have not explored the full suite of opportunities available to regulate and monitor the effectiveness of existing policy ordinances.
- The status of the environment and resources relative to the existing thresholds is largely unknown.

Agency identification of key management questions of specific interest and their relationship to short- and long-term goals based on specific management objectives is lacking.

- Although a number of basinwide key management questions have been identified, each agency appears to have its own specific issues, goals, and agendas. These are often conflicting and repetitive when separately addressed.
- Reexamination of the historical application of model-based policy is important, particularly in the context of new quantitative data and technologies. The foundation for current thresholds appears to reside in part within the context of the original Bailey Land Capability Classification (Bailey 1974). The Bailey system was based on the original "Tahoe Basin Soil Survey, California and Nevada" (USDA SCS and FS 1974), which has now been updated by the "Soil Survey of the Tahoe Basin Area, California and Nevada" (USDA NRCS 2007). We suggest this classification system and any related thresholds be reevaluated in the context and guidance of findings presented in the new Soil Survey

Underlying ecosystem processes of relevance to soil conservation are largely unknown, and such knowledge would help to facilitate the broad application of adaptive management strategies across projects within and among contributing watersheds.

- Clear identification of where research and agency monitoring programs can be strengthened and integrated would benefit from full assessment. To implement more cost-effective data collection, better integration of science information (i.e., research and monitoring) into the decisions affecting the implementation of capital programs is recommended.
- There is no standard method of measurement and monitoring protocols from which data reporting and interpretive analysis can be applied basinwide. This makes it more difficult to compare results from different activities or similar activities at different locations throughout the basin.

The decrease in Lake Tahoe's clarity has been largely attributed to a combination of fine sediment suspension and enhanced biomass production from N and P nutrient loading.

- Most published erosion control studies in the basin have focused on reporting total sediment yields alone. More work is specifically recommended to determine how erosion control measures affect fine sediments and their related equilibrium nutrient chemistry. One erosion control study reporting on nutrients and fine sediment showed erosion control structures to be effective in removing coarse particulates, but not nearly as effective when dealing with fine sediments and nutrients (Garcia 1988).
- Which colloidal-size particles, their associated mineralogy, and their equilibrium chemistry are most important to bio-available nutrient contributions and physical light scattering remains unknown. Better quantitative evaluation in this regard is critical to the development of programmatic, investigative, and management approaches that focus on what the literature now indicates as contributors to diminished water clarity.

Revegetation of unstable slopes has had mixed success owing to a lack of uniform application of approaches that are based on well-founded principles.

- Revegetating slopes has been more costly owing to the rarity and unpredictable availability of native vegetation seed stock and seedlings in nurseries.

Broader knowledge of the overall effectiveness of multiobjective BMPs applied in the Tahoe basin is needed to educate the public and evaluate the suitability of regulatory policy.

- Published research on basinwide BMP effectiveness is limited.
- Although BMP effectiveness research is currently being performed by several agencies in the Tahoe basin, consistency in parameter measurement and reporting of results is seldom achieved (Lynard et al. 1980, Schuster and Grismer 2004).

Best management practice effectiveness is usually tested as a whole for several BMPs implemented on one site.

- Determining which BMPs are truly the "best" would require (1) matching the correct BMP to site conditions and (2) testing them against one another rather than comparing their cumulative site effects.
- Collective BMP effectiveness in different situations and combinations has not been evaluated.

Urban development and anthropogenic activities typically reduce native soil capacity.

- BMPs for protecting and rehabilitating soils affected by urbanization are not well defined in terms of design, function, or effectiveness.

Erosion control structures are being implemented throughout the basin on construction sites and residential and commercial lots.

- The number of erosion control structures actually monitored for compliance and effectiveness is unknown.
- Whether or not appropriate structures are being implemented in each site and location is uncertain.

It has been suggested that many temporary sediment traps used on construction sites are frequently installed incorrectly.

- Regular inspection of construction sites for compliance and real-time enforcement would assist in the performance evaluation of management strategies.
- Inspection, maintenance, and enforcement of monitoring protocols as outlined in the SWPPP would be helpful.

Wood fiber, pine needles, and other organic materials are frequently used as mulch when stabilizing bare soils.

- Thick pine needle mats have been shown to be a possible contributor to high levels of biologically available N and P in surface runoff.
- Little is known about the nutrient release effects of woodchips when used as mulch layers or when incorporated into the soil.
- The creation of defensible space through vegetation management usually means reducing the amount of fuel around the building or structure, providing separation between fuels, or reshaping retained fuels by rearranging the trees, shrubs, and other fuel sources such as plant-residue groundcover in a way that makes it difficult for fire to transfer from one fuel source to another.
- Vegetation removal for defensible space can cause soil disturbance, soil erosion, regrowth of new vegetation, and introduce nonnative invasive plants. Areas up-gradient of water riparian areas, such as streams or ponds, are a particular concern for protection of water quality when developing a defensible space protocol.

Tahoe Regional Planning Agency threshold standards remain in nonattainment status.

- Goals for the attainment of established threshold standards continue to be set, but it remains difficult to achieve attainment.
- Threshold indicators are typically monitored for attainment only, and not for determining the effectiveness of the threshold in protecting Lake Tahoe water quality.

The application of new knowledge to improve management policies and practices would require active communication between researchers and policymakers.

- Some agencies may be diligent in their monitoring and integration of results into management decisions, whereas others may not be so diligent.
- There is inconsistency regarding the incorporation of pertinent new findings into the policymaking process.

Research Needs

- Include N and P nutrient forms, fine sediments, and their associated equilibrium chemistry as specific parameters in quantitative analysis for BMP, SEZ restoration, and impervious coverage reduction effectiveness studies.
- Develop standardized monitoring protocols for the monitoring of BMP effectiveness, SEZ restoration, and impervious-coverage reduction in the Tahoe basin. Findings could then be reported in peer-reviewed journals for enhanced credibility.
- Measure the effectiveness of BMPs as separate entities rather than a program as a whole. Similar slope stabilization, infiltration, or sedimentation techniques could be tested against each other in similar and divergent environments as a means of ascertaining why some work better than others in one locale vs. another.
- Determine the depth of understanding and actual participation of Tahoe basin residents in the maintenance of their privately managed BMPs.
- Monitor and compare several combinations of BMPs in a variety of settings, including urbanized sites. This creates the perfect scenario in which to investigate the range of functions for commonly applied BMPs in the Tahoe basin and their ability to protect and restore important soil properties such as infiltrability, stability, soil moisture storage, and capacity to support revegetation. This could also be used to determine compliance maintenance schedules for BMP upkeep.

- Monitor construction sites to determine compliance and ability to effectively install and maintain temporary BMPs.
- Conduct research to quantitatively demonstrate how sound adaptive management practices, even at the individual scale (e.g., homeowner BMPs), benefits and enhances the Tahoe basin environment and improves water quality.
- Develop a horticulture program geared toward the propagation, seed bank development, and seedling establishment techniques for native vegetation to stabilize slopes in the Tahoe basin.
- Monitor established environmental thresholds to assess attainment as well as effectiveness. Realistic goals could then be set for attainment of these thresholds when proven effective in the reduction of nutrient and sediment loading to the lake and the enhancement of water clarity.
- Quantitatively compare Bailey's Classification System and the IPES to naturally functioning systems with no impervious coverage to determine the level of effectiveness the reduction in impervious coverage is having. Furthermore, these studies could assist in integrating information from the new soil survey into these existing systems, and reassessment research could be performed to better understand the regulatory implications of any new findings.
- Determine the potential social and environmental benefits of relocating existing land coverage to hillsides or intervening zones having equal or greater infiltration capacity, deeper ground water, and greater potential for subsurface filtration.
- Research and monitor existing regulatory programs such that their true effectiveness and applicability can be more quantitatively assessed. Research on BMPs and regulatory programs from other areas may be beneficial.
- Reevaluate or monitor the use of wood fiber, pine needles, and other organic materials and its relationship to defensible space, overall applicability and site-specific effectiveness.
- Compile comprehensive data syntheses of results from previous findings and also current research projects, monitoring programs, and impending adaptive management strategies. A single database would be the optimal place to look for environmental information, management strategies, and problem-solving options in the Lake Tahoe basin.

- A standard protocol for the measurement and monitoring of Tahoe basin (eastern Sierran) ecosystems is recommended. Use of these protocols by all Lake Tahoe basin participants would facilitate the comparison of basin-wide soil conservation projects and the compilation of results from projects conducted at different locations by different institutions and/or the private sector.

Near-Term Soil Conservation Research Priorities

Following are a prioritized listing of the three most immediate near-term soil conservation research needs within each subtheme category. This approach was taken because different agencies may be more focused on the components of a given subtheme rather than the broader category of Soil Conservation as a whole.

Key Soil Properties and Conditions (SPC)

Research Priority No. 1 (SPC1): Further quantify the distribution of various watershed properties such as soil water repellency, biologic and inorganic nutrient pools, infiltrability, and water balance parameters on a larger spatial scale. The impact of natural and anthropogenic activities such as development (impervious vs. pervious), forest management (fire suppression vs. mechanical or prescribed fire biomass reduction), vegetation (native vs. non-native species), restoration (physical and chemical amendments vs. reduced fertilization), and features that have disrupted natural littoral and eolian processes on soil health at the watershed scale (including the intervening zones) remains poorly understood.

Research Priority No. 2 (SPC2): Assess which restoration methods are most effective in controlling event-based runoff. Also, the transport and equilibrium chemistry of fine particles most associated with nutrient and sediment loading should be more quantitatively assessed. Project success and longevity should be evaluated relative to the sustainability of hydrologic function, productivity, and erosion control over time.

Research Priority No. 3 (SPC3): Characterize to the extent feasible and quantify where possible, historical vs. current and natural vs. anthropogenic induced declines in soil status and resulting soil loss at the watershed scale. Research on soils in natural as well as disturbed settings is recommended whenever possible, with sites established to measure soil conservation parameters including inputs such as plant-soil nutrient fluxes through litter-fall, crown-wash, and root turnover as well as losses from erosion, leaching, runoff, wind, or fire. Research would focus on sites where a suitable control portion is available, especially if event (e.g., prewildfire or pretreatment) data are available.

Knowledge advancement potential—

The fate of Sierran ecosystems in a changing environment will have a direct impact on soil health, fire hazard, biomass mitigation strategies, erosion, and water quality. Manipulative research projects that include random assignment of treatments and replication are challenging to perform in the Tahoe basin. And yet a crucial research need is to identify and quantify key indicator parameters in a variety of historical and current ecological settings, under various manipulations, and over time. In such cases where robust experiments are possible, restoration methods that are most effective in controlling runoff and transport of fine particles, as well as those most effective in the reduction of nutrient discharge loading and its direct effect on water clarity, can be better assessed. This would allow a more complete understanding of the environmental factors (i.e., temperature, moisture, vegetation, and litter) that determine the formation, persistence, and dissipation of seasonal and long-term effects on runoff water quality and erosion. In this context, similar slope stabilization, infiltration, revegetation, or sedimentation techniques could be tested against each other in similar and divergent environments as a means of ascertaining why some work better than others in one locale vs. another. Research focused on the identification, monitoring, evaluation, tracking, and adaptive management of individual and collective BMP systems—and linking them to GIS layers at the watershed and basin scale—would go a long way toward addressing the concerns of stakeholders and agencies alike. Being able to track and revisit BMP strategies would further facilitate true adaptive management.

Development and Application of Predictive Models (PM) as Related to Soil Conservation

Research Priority No. 1 (PM1): Successful model application dictates the need for site-specific parameterization and model calibration. Model use and application can then become more consistent and interpretive assessment more uniform among agencies basinwide. Research and monitoring protocols are recommended to provide relevant information for predictive model development, improvement, calibration, and field validation specific to the Lake Tahoe basin. A prioritization of which soil, vegetation, and hydrologic parameters are important, what should be measured, and what information is needed to parameterize and calibrate the models should be established.

Research Priority No. 2 (PM2): Develop a spatially explicit water balance, nutrient cycling, and erosion potential model to better understand current sediment and nutrient transport at the watershed scale and under conditions of potential changes in hydrologic and soil parameters. The role of hydrophobic soils should be further studied to determine the spatial distribution of recharge areas vs. those that are overland flow generating and their influence on soil erosion model output estimates. A prioritization of which parameters are important, what should be measured, and what information is needed to parameterize and calibrate the models should be established.

Research Priority No. 3 (PM3): Develop a better understanding of how various factors or stressors change soil status in Tahoe basin watersheds to assist forest managers in preparing management plans and make predictions about ecosystem response to natural (e.g., fire, insect attack, drought, or erosion) and anthropogenic (air pollution, harvesting, development, or climate change) perturbations. For example, a comprehensive assessment of the effects of both wildfire and prescribed fire, and postfire vegetation, on long-term response in biological and physicochemical soil parameters is needed to better understand fire and its role in restoration ecology.

Knowledge advancement potential—
Because regulatory policies may be based on the subjective judgment of "risk potential" rather than on a sound quantitative decision-support system, the application of predictive models can provide important tools to understanding and estimating the potential outcome of management strategies and programs. Successful model application, however, is accomplished through site-specific parameterization and model calibration. Establishing a means for prioritizing which ecosystem parameters are important, what should be measured, and what information is needed to parameterize and calibrate the models. In the event that the current models are not adequate predictors, appropriate modifications or adjustments are needed to make the existing models more functional. If this is not an option, starting from scratch and developing a new model that is simple, accurate, and appropriate for the Tahoe basin may be necessary. Model use and predictive application is recommended to enable consistency among agencies basinwide wherein the acquisition of a more robust quantitative database could provide the foundation for policies of future management strategies.

Effects of Climate Change (CC) as Related to Soil Conservation

Research Priority No. 1 (CC1): There is concern that anthropogenic activities over the last century have resulted in nontypical ecosystem structure throughout the basin of which the distribution, character, variability, and potential response to climate change have not been evaluated. Consequently, strategic efforts directed toward long-term site restoration in response to a quasi-natural state will be the more likely scenario. Quantitative assessment of what we can and cannot hope to accomplish on a long-term basis is recommended.

Research Priority No. 2 (CC2): More comprehensive localized point source precipitation, surface runoff, erosion, and nutrient transport data is recommended to quantify potential discharge loads as a function of amount, type (snow vs. rainfall), frequency, and precipitation intensity. Research and monitoring projects should be designed to address potential changes in hydrologic parameters as a result of climate change.

Research Priority No. 3 (CC3): Investigate the implications of climate change on slope stability parameters. Surface soil stability, compaction, soil structure and aggregate stability, infiltrability and runoff, and potential for mass wasting should all be tested under scenarios of different temperature and moisture regimes to estimate the potential effects of climate change on soil erosion in the Lake Tahoe basin.

Knowledge advancement potential—

The implications associated with climate change cannot be ignored. Predictions for changes in precipitation quantity and intensity are quite variable for the Sierra Nevada. One scenario is that precipitation will increase in intensity leading to large-scale flooding. Another is that the Lake Tahoe area will be subject to overall warmer temperatures and more evapotranspiration, whereas increased precipitation will be more common farther to the north. There is general agreement, however, that with warmer temperatures, snow elevation levels will be higher with less accumulation, which will lead to longer fire seasons. New approaches are recommended for examining shifts in the quality and amount of hydrologic inputs to support management strategies involving biomass reduction, drainage control, and practices to diminish sediment and nutrient transport to Lake Tahoe. It is recommended that future planning for the production of resilient, spatially heterogeneous and diverse forest structure be designed to account for potential changes in hydrologic function in response to different moisture regimes to determine what the ultimate effects of climate change could be on management protocols for sensitive areas at the watershed and locale scales.

Policy Implications (PI) and Adaptive Management Strategies as Related to Soil Conservation

Research Priority No. 1 (PI1): Monitor and study established environmental thresholds for attainment and for performance effectiveness. It is recommended that regulatory agencies and land managers develop a protocol for periodic review, verification, and update of processes, quantitative thresholds, and policy relevance.

More research and monitoring of existing regulatory programs is recommended, such that their overall effectiveness and applicability can be more quantitatively assessed relative to their actual reduction of nutrient and sediment loading to the lake and the subsequent enhancement of water clarity. Develop a basinwide protocol for "Standard Methods of Ecological Measurement and Monitoring in the Tahoe Basin."

Research Priority No. 2 (PI2): Continued research that addresses critical natural resource issues and critical management questions relevant to soil conservation in the Lake Tahoe basin is essential. This exercise can begin by identifying a list of agency-specific management questions pertinent to soil conservation relative to key soil properties and conditions of interest. For example, what are the appropriate management strategies that maximize defensible space protection, but at the same time function to minimize erosion and the degradation of runoff water quality? It is then important to take advantage of unique opportunities and small-scale experimental field trials to quantitatively evaluate potential impacts. To ensure its credibility and applicability, such research would make every effort to be scientifically defensible, applicable to the Tahoe basin or similar ecological settings, and publishable in peer-reviewed journals.

Research Priority No. 3 (PI3): Restoration and BMP strategies are generally implemented to mitigate known adverse impacts from either natural events or anthropogenic activities. Choosing the most effective strategy therefore will benefit from a thorough knowledge of the mitigation objective, process mechanics, both short- and long-term functionality, and whether or not these components will differ depending on location within a given watershed or the Tahoe basin in general. Performance evaluation is commonly assessed on a collective (e.g., projectwide) rather than individual (e.g., specific management activity) process basis. Complete evaluation of which strategies are truly the most effective in meeting specific restoration objectives would require testing each management activity against one another as well as assessing their cumulative effects. Management strategies implemented for one purpose (e.g., defensible space) may or may not have an effect on other issues of concern and ascertaining why some work better than others in one locale vs. another (or not at all) is a critical issue.

Knowledge advancement potential—

If greater confidence in performance effectiveness can be developed, consistency will likely follow. With new technology comes the opportunity for innovative soil conservation strategies that could alter or refine historical threshold values. In the past, technological advancement and expansion of the knowledge base was much slower. Today, it is not unusual for substantial new advancements to take place on a 5-year rather than a 25-year cycle. Key to the success of any such approach, however, is the development of a consistent and effective monitoring protocol for key soil properties and conditions that is current, process-specific, and uniform across agencies and contractors. Hence, research is recommended to develop a standard protocol for ecological measurement and monitoring in the Lake Tahoe basin, which includes variable levels of intensity that can be applied to different types and scale of projects. In its absence, implementers and agencies frequently employ different techniques in attempting to evaluate the performance effectiveness of similar soil conservation activities. Comparative interpretive assessment is then difficult to impossible. Furthermore, evaluating which conservation and/or restoration methods are most effective is recommended in the context of a more comprehensive framework wherein each on-the-ground management strategy could be tested against one another in similar and divergent environments. Therein, lay key opportunities where new and unique soil conservation strategies could be explored. Finally, agency representatives can clearly identify agency-specific areas of concern, and then work with scientists and implementers to articulate the respective critical soil conservation issues. This would greatly assist in the development and design of successful monitoring, opportunistic, and/or experimental research programs that generate data and information directly applicable to agency needs.

English Equivalents:

When you know:	Multiply by:	To get:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	.394	Inches
Meters (m)	3.28	Feet
Hectares (ha)	2.47	Acres
Square meters (m^2)	10.76	Square feet
Cubic meters (m^3)	35.3	Cubic feet
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit

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Chapter 6: Ecology and Biodiversity[1]

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Introduction

The integrity of animal and plant communities serves as a critical measure of the effectiveness of policies designed to protect and restore ecosystem processes in the Lake Tahoe basin. The conservation of plants and animals in the Tahoe basin is utterly dependent on the conservation of its terrestrial and aquatic ecosystems; so, in many ways, the research agenda that follows builds on the other research described in this volume. Accordingly, successful integration of outcomes from research on water quality, air quality, and other natural attributes of the basin will contribute greatly to the recovery and persistence of biological diversity in the Tahoe basin.

A Lake Tahoe research agenda that considers biological diversity and ecological function is best based on data collected from across scientific disciplinary boundaries. In Tahoe's intensively managed forests, there is an immediate and keen interest in linking forest fuel treatments to changing soil conditions, vegetation composition and structure, and the status of wildlife populations at multiple trophic levels. That immediacy noted, the Lake Tahoe basin actually is home to remarkably few imperiled species; however, that could change in short order through well-intended land and resource management actions that lead to unanticipated species declines (Manley 2005). Little species-specific information is currently available to guide land use and resource planning should changed circumstances lead to new listings under federal or state endangered-species statutes.

A number of policies direct and define management objectives for biological diversity in the Lake Tahoe basin. The Lake Tahoe Environmental Improvement Program identifies multiple restoration actions that are expected to benefit wildlife. Documents supporting the Tahoe Regional Planning Compact (1969), namely the 1987 Regional Plan (see http://www.trpa.org), call out 20-year goals for wildlife and

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fish, and identify environmental thresholds, indicator measures of those thresholds (including species indicators), and species and communities of special concern. The National Forest Management Act (1976) directives pertain to plants and animals on the more than 70 percent of Tahoe basin lands under U.S. Department of Agriculture, Forest Service jurisdiction. The U.S. Department of the Interior, Fish and Wildlife Service implements focal activities associated with several wildlife, fish, and plant species on National Forest System lands in the basin. Provisions of the Migratory Bird Act pertain to the entirety of the Lake Tahoe basin. Stringent state lands and parks rules are enforced on both California and Nevada sides of the lake. And both federal and state wildlife agencies are able to implement prohibitive policies if a threatened or endangered species listing becomes necessary.

Despite a demonstrated concern, our understanding of nearly all aspects of Lake Tahoe's biodiversity—from species found in lakeside meadows, to those on alpine peaks above—is still rudimentary and would benefit greatly from implementation of the research agenda that follows. To varying degrees, management of all Tahoe basin ecosystems would be better informed by improved scientific knowledge about ecological characteristics, habitat associations, and species responses to management activities. Detailed status and management response information is available for very few species in the basin; and, in most management applications, it will be necessary to know the local status and responses to management given the unique configuration of wildlife habitats within the basin, and the basin's relative isolation from the larger forested landscape of the Sierra Nevada. To that end, this chapter identifies focal management issues, associated uncertainties, and key research questions that, if answered, would encourage effective, efficient, and accountable resource management designed to maintain and conserve biological diversity, ecological function, and ecosystem services. Research in the Lake Tahoe basin will be most effective when designed in a manner that both decreases resource risk and uncertainty by closing information gaps, and directly informs management. For example, a research program to address uncertainties about the effects of forest management on biological diversity might start with a description of site-scale response patterns of biological diversity to various environmental changes associated with forest management. This program also might take steps to apply those data to the development of management tools that:

- Apply that understanding to the basin as a whole to inform management about conditions throughout the Lake Tahoe basin.
- Identify system indicators that can be used to monitor progress toward management goals for forest ecosystems.

- Determine thresholds of species and community responses that can inform how and when management actions should respond to monitoring results.
- Provide evaluation tools that managers can use independently.
- Provide basic data to enhance management and policy development.

The ecology and biodiversity research agenda considers seven subthemes that represent various management activities and objectives: (1) old-growth and landscape management, (2) fire and fuels management, (3) special community management, (4) aquatic ecosystem restoration, (5) urbanization, (6) recreation, and (7) climate change. Within each subtheme, we provide a summary of issues and uncertainties and associated key research questions. The departure from historical conditions reflected in current ecosystem conditions in the basin presents many challenges to restoration. Most fundamental is the challenging fact that existing terrestrial and aquatic ecosystem conditions are unique in the history of the basin as are the current and projected future climate conditions. Thus, the objective of restoration is not to return these systems to an historical structure or composition, but rather to restore their biological diversity, function, and resilience. The key research questions span many types of information gaps including basic information gaps; effects and effectiveness of existing management approaches; models of past, current, and potential future conditions; and field and analysis tools to enhance the "toolbox" of methods available to managers to inform planning and decisionmaking.

The ecology and biodiversity research agenda highlights the interactions between native species and communities and natural and human-caused stressors that present the greatest ecological and social risk, and for which research can reduce management-related uncertainties. Conceptual models are provided that show the primary linkages between native species and communities as components of ecosystems and the factors that affect their condition, including human-caused stressors (figs. 6.1 and 6.2). The two conceptual models group subthemes that share most of the same components and drivers: terrestrial ecosystem subthemes (old-growth forests and fire and fuels management) (fig. 6.1), and primarily aquatic ecosystems subthemes (special communities and aquatic ecosystems) (fig. 6.2).

The subthemes identified in the ecology and biodiversity theme area represent focal elements for management planning and action in the Lake Tahoe basin (figs. 6.1 and 6.2). The core components are those shared by most biological systems (e.g., species composition and abundance, vegetation structure), with differences expressed in the specifics of the components (such as associated species). The primary drivers of the condition of components also are often shared, given that human activities are pervasive and affect many biological components. Secondary

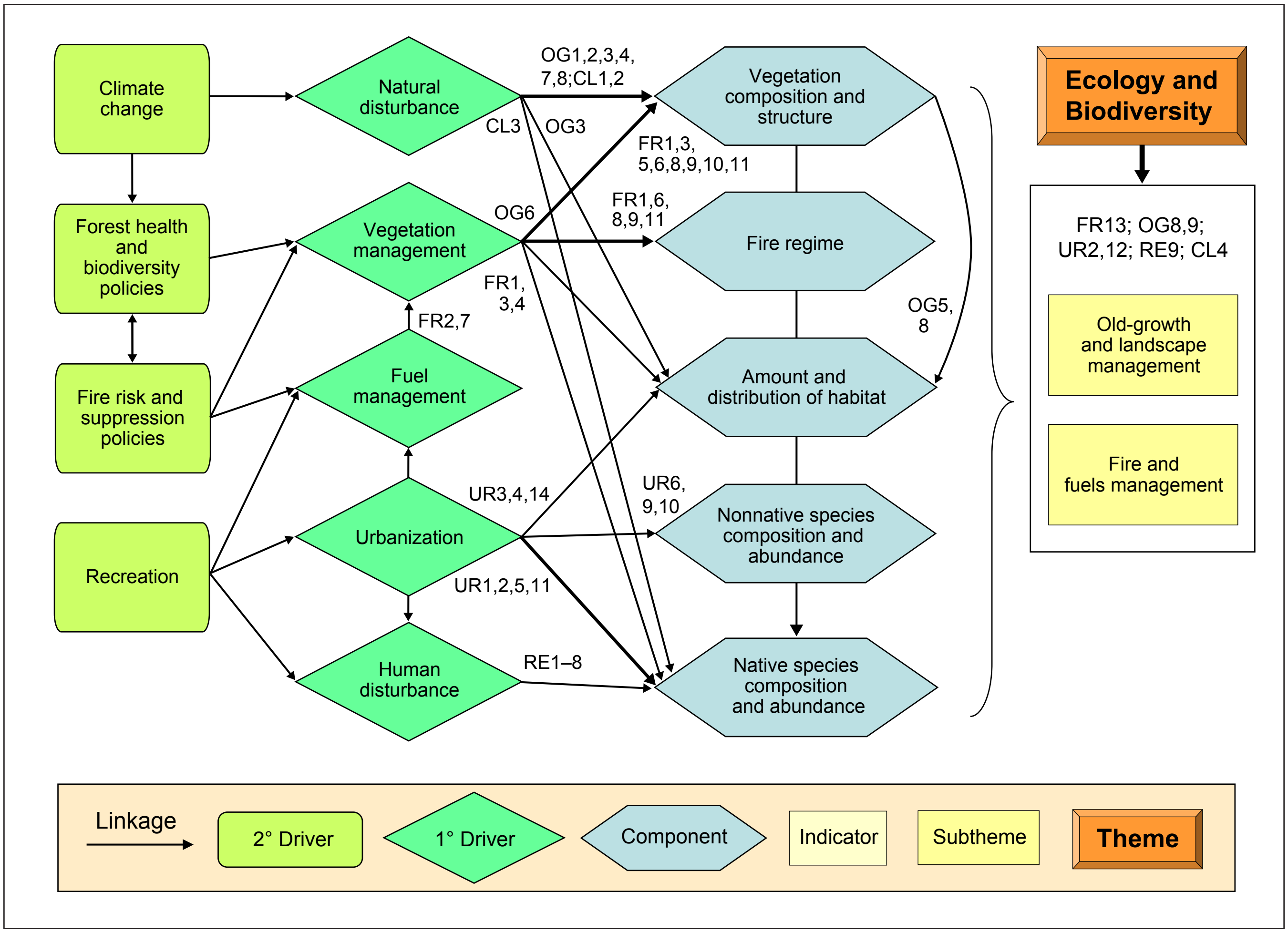

Figure 6.1—Conceptual model of the terrestrial ecosystem subthemes in the Ecology and Biodiversity theme. Identified are the primary components of terrestrial ecosystems in the Lake Tahoe basin, the natural and human-caused phenomena that affect their conditions, and the focus of research questions in the theme area, which are based on management concern and uncertainty. Thick arrows indicate especially important linkages between drivers and components. Research needs are indicated by alphanumeric symbols (e.g., CL3, OG3) and correspond to the descriptions presented later in the chapter.

drivers are typically external, broad-scale forces that act on human activities, such as regulations, policies, economic forces, and climate. It is important to recognize that stressors may have initial positive consequences for some species (e.g., habituation to human settlement by bears and geese) that then lead to undesirable secondary consequences (e.g., property damage or reduced diversity of native species).

The majority of uncertainties associated with terrestrial ecosystems pertain to the linkages between vegetation management and climate change (i.e., natural disturbances) and their effects on vegetation structure, composition, and associated fire hazards (fig. 6.1). A more limited set of questions pertain to the effects of forest fuels treatments on plant and animal communities, populations, and habitats. The

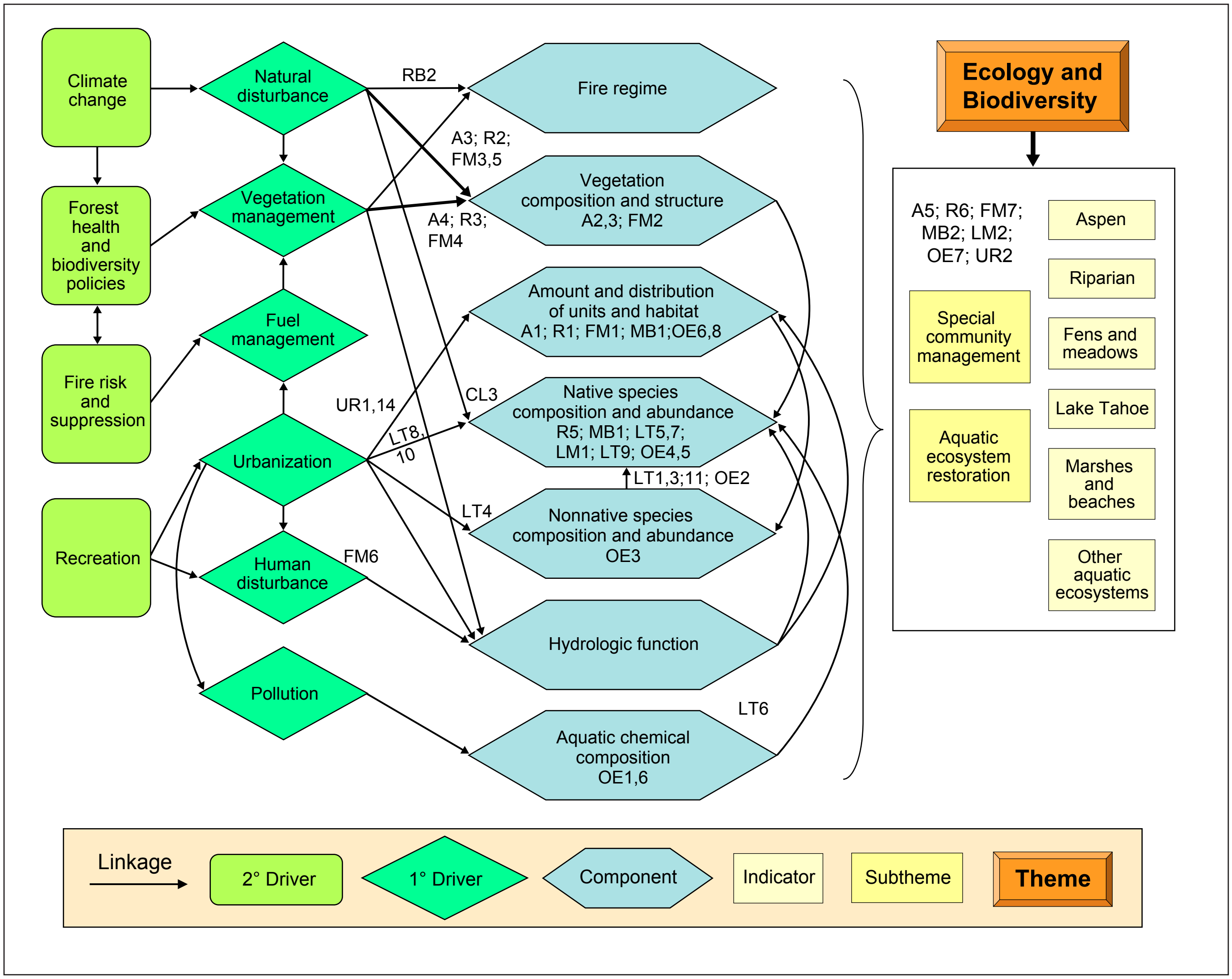

Figure 6.2—Conceptual model of the aquatic ecosystem subthemes in the Ecology and Biodiversity theme. Identified are the primary components of aquatic ecosystems in the Lake Tahoe basin, the natural and human-caused phenomena that affect their conditions, and the focus of research questions in the theme area, which are based on management concern and uncertainty. Thick arrows indicate especially important linkages between drivers and components. Research needs are indicated by alphanumeric symbols (e.g., R2, FM3) and correspond to the descriptions presented later in the chapter.

limited set of questions regarding biodiversity does not reflect lower uncertainty and risk, but rather it reflects the priorities of management, and the assumption that fuels treatments will not substantially alter the habitats of animals and herbaceous plants. Land and resource managers are interested in identifying key measures of conditions that can be used as indicators for progress toward desired conditions. These circumstances are not unique to the terrestrial ecosystems or the ecology and biodiversity theme; rather they recognize an area of substantial investment by management agencies at the present time.

The majority of uncertainties associated with the special communities and aquatic ecosystems are weighted toward basic information, as opposed to linkages between activities and the condition of components (fig. 6.2). This is a function of limited investment in research and monitoring in aquatic ecosystems other than Lake Tahoe itself; so it is generally thought that basic information on current conditions is the first step toward informing management. Not all special communities are identified, but the suite that is identified represents those of greatest management interest. In addition to the pursuit of basic information, greater understanding is needed about the linkages between natural disturbances, and the role of fire and fuels reduction on vegetation composition and structure, particularly in riparian and meadow habitats. As with terrestrial ecosystems, indicators would be selected for the purposes of assessing the condition of each of the special communities and aquatic ecosystems.

The research questions that are identified here constitute the highest priority information needs over the next 10 years, based on the combination of three considerations: (1) uncertainty based on lack of knowledge, (2) current risk based on the current condition of biophysical components, and (3) potential future risk based on current or future management activities or climate change. The questions represent those that, if addressed through research, would make a substantial contribution toward reducing uncertainty and risk in conservation and restoration efforts targeting biological diversity and ecological integrity in the Lake Tahoe basin. Some of the questions presented are more time sensitive than others, either as a function of their placement in a sequence of discovery or the ease of answering the question relative to the value of the contribution to reducing uncertainty and risk. The most time-sensitive questions within each subtheme are indicated in bold.

Old-Growth and Landscape Management

Past management activities, particularly historical logging, followed by fire suppression, substantively shaped the amount, distribution, and condition of old-growth forests in the Lake Tahoe basin today. Current management activities continue to affect the character and distribution of the basin's forest ecosystems. The combination of these anthropogenic and natural disturbances has determined the current distribution of seral conditions across the basin, including the distribution and abundance of the remaining old-growth forest patches (Manley et al. 2000). Forests in the Lake Tahoe basin now differ in a number of important aspects from their pre-Euro-American appearance. In the montane zone, the tree species composition and diameter distribution have changed greatly; there are far more small-diameter trees (e.g, < 30 cm diameter at breast height [DBH]) of shade-tolerant species (particularly white fir, *Abies concolor* (Gordon & Glend) Lindl ex Hildebr.) in the understory than there were formerly, and far fewer larger-diameter (e.g., ≥ 75 cm DBH), older trees (Barbour et al. 2002). Moreover, the proportion of the landscape in montane chaparral has diminished, having been converted to forest (Nagel and Taylor 2005). Both of these changes indicate a reduced proportion of the landscape in both early and late-successional stages relative to the pre-Euro-American Tahoe basin landscape. The majority of the landscape is single-aged, fire-suppressed, second-growth fir and pine, a condition that would not exist historically.

Knowledge Gaps

The departure from historical landscape conditions in the Tahoe basin resulting from timber harvest and fire suppression has contributed to a reduction in terrestrial biodiversity, as well as apparent increases in fire risk (Weatherspoon and Skinner 1996). Debate exists regarding the extent of old-growth forests that historically occurred in the basin. A better understanding of historical old-growth reference conditions could help in assessing how the basin has changed over time, what those changes represent in terms of accompanying plant and animal diversity, and what targets might be set for future conditions in terms of the extent and condition of old-growth forests in the basin (Manley et al. 2000).

Seth Bigelow

Old-growth mixed-conifer stand in the Upper Truckee watershed, Lake Tahoe basin (2006).

Central questions for Lake Tahoe basin forest managers pertain to how much of various forest conditions is desired, and how those conditions should be distributed spatially to ensure the persistence of associated species, functions, and services. A well-defined vision for desired conditions can be used to design forest management and speed the transition to desired conditions; alternatively, forest management lacking such a vision can impair progress toward desired conditions. Agency managers in the basin have identified species of special concern and interest. For example, species of special concern identified in the Pathway planning process that have an association with old-growth forests include northern goshawk (*Accipiter gentilis*), American marten (*Martes americana*), pileated woodpecker (*Dryocopus pileatus*), and California spotted owl (*Strix occidentalis*). Other species of concern associated with old-growth components include osprey (*Pandion haliaetus*), bald eagle (*Haliaeetus leucocephalus*), and black bear (*Ursus americanus*). The population of brown-headed cowbird (*Molothrus ater*), another species of concern based on its potential ecological impact, is also affected by forest management practices. Coyote (*Canis latrans*) and black bear are species of high public interest in the basin (Manley et al. 2000); their populations are likely to change in response to forest management, and given their status as top carnivores in the basin, changes in their populations are likely to precipitate changes in wildlife community composition and structure (Crooks and Soule 1999).

There are many areas in the basin that cannot support certain forest structural conditions owing to physiographic constraints, such as slope, aspect, elevation, and soil depth, which affect vegetation growth rates and disturbance regimes (Taylor and Skinner 1998, Urban et al. 2000). Vegetation growth models can help define how those structural conditions will change over time across the basin, but a concrete understanding of how landscape configuration constrains the basin's vegetation communities is needed.

Disturbance fundamentally shapes forest structure and species composition in the Lake Tahoe basin. Current management activities with the greatest potential to affect old-growth forest vegetation conditions and landscape configuration are fuel treatments, fire suppression activities, and salvage logging. Wildfire, avalanches, and landslides are the most common natural disturbances shaping forest structure in the basin. Although we now understand the fundamentals about the role of fire in maintaining historical vegetation structure in the basin (Scholl and Taylor 2006, Taylor 2004, Taylor and Beaty 2005), relatively little is known about the role of avalanches and landslides, and their interactions with fire regime. Avalanches can break up landscape-level fuel continuity, and conversely, forested areas diminish avalanche risk (Kattelman 1996). A better understanding of the basin's natural disturbance regimes and their interactive effects would aid forest restoration efforts. Recreation activities, both motorized and nonmotorized, can greatly affect the occurrence and abundance of wildlife species and thereby the structure of animal communities. Thus, recreation represents an added source of disturbance to wildlife, and its management is relevant to achieving desired forest conditions.

Research has begun to examine how forest restoration planning should consider a changing climate regime (Harris et al. 2006). Most research suggests that by the year 2070, a mean increase of two to five degrees centigrade in June–August temperatures will manifest in the Western States (Running 2006). This dramatic temperature change, and attendant changes in the hydrologic cycle, will predispose the basin to more extensive and intense wildfires (Taylor and Beaty 2005, Westerling et al. 2006) and change the distribution and interactions among plant and animal species. This means that desired-condition decisions and associated management strategies now informed and shaped by historical reference conditions also could be informed by current and projected future climatic conditions and disturbance regimes.

These issues and uncertainties translate into the following broad management questions:

- What stand conditions should management create to ensure that forest health and resilience is restored in the future?
- How much and where should various stand conditions be located throughout the basin to ensure that populations and communities of native plant and animal species are maintained?
- What key measures of stand conditions and landscape configurations will be most effective and efficient in monitoring forest ecosystem health and informing forest management?

Research Needs

In the subsequent research needs sections, and figures 6.1 and 6.2, research questions are identified by combined text and numeric codes. Text codes are defined as follows: OG for old-growth and landscape management; FR for fire and fuels management; FM for fens and meadows; A for aspen; R for riparian areas; LM for lakeside, beach, and marsh; LT for Lake Tahoe aquatic ecosystems; OE for other aquatic ecosystems; UR for urbanization; RE for recreation; and CL for climate change. Numbers refer to the sequence of questions presented in each subtheme. Bold codes indicate the most time-critical research needs.

Following are the old-growth and landscape management research questions:

(**OG1**) What more can we learn about pre-Euro-American settlement (prior to 1850) characteristics of forests in the Lake Tahoe basin with respect to plant species composition; diameter distribution of trees, snags and logs; and proportional representation of seral stages? How did these characteristics differ according to topographic position (slope, aspect, and elevation), longitude, and soil substrate? What is the relationship between historical stand structure and composition, and existing map products depicting "potential natural vegetation?"

(**OG2**) Does the condition of the pre-Euro-American settlement forests in the Tahoe basin represent a satisfactory model for forest restoration (i.e., desired future condition), and if not, how should it be modified to account for factors such as climate change and irreversible changes in land use? What are the projected changes in range and elevation of dominant tree species within the Tahoe basin owing to climate change?

(**OG3**) How did the historical disturbance regime (e.g., fires, landslides, avalanches, insect outbreaks) differ spatially, in intensity and extent, within the Tahoe basin? How did these disturbances shape the structure and composition of the forest? Did upper and lower elevation zones exhibit different spatial patterns of disturbance and resulting structure?

(**OG4**) What animal species are most closely associated with old-growth forests in the basin, and what are the relative effects of different stand conditions and landscape configurations on the persistence of these species and biodiversity, with particular emphasis on special-status species? How do closely associated species use old-growth stands, compared to other available areas, for foraging, shelter, dispersal, and reproduction, and what are the most favorable amount and configuration of forested conditions to support forest biological diversity and special-status species?

(OG5) What were and are the effects of historical logging and fire suppression on forest-associated wildlife species, including composition, abundance, co-occurrence, and diversity?

(OG6) What are the likely spatial changes in range and elevation of sentinel animal and plant species (i.e., species that are sensitive indicators of change) within the Tahoe basin in response to climate change?

(**OG7**) What elements of old-growth forests are key to maintaining their biological diversity (including density of large trees, basal area, stand contiguity, tree age structure, or standing or fallen large woody debris)? What is an effective set of indicators of the physical and biological conditions of old-growth forests?

(**OG8**) What performance measures—including presence and abundance of plants and animals, and other ecological community metrics—can be used to assess the effectiveness of efforts to restore historical (or achieve desired) old-growth forest structure, composition, and function?

(**OG9**) What landscape features and locations (e.g., dispersal/migration corridors) play key roles in maintaining populations within the basin, and what species or measures can serve as indicators of the function of these key features?

Fire and Fuels Management

Fire was undoubtedly the most pervasive agent of ecological disturbance in the Lake Tahoe basin prior to its settlement by Euro-Americans in the latter half of the 1800s. Reconstructions of the presettlement fire regime from cross-dated fire scars in old stumps and logs have shown that the historical fire-return interval ranged from an average of about 11 years in Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and white fir forests (Taylor 2004), to 28 years in montane chaparral stands (Nagel and Taylor 2005), to 76 years in high-elevation red fir (*Abies magnifica* A. Murr.) and western white pine (*Pinus monticola* Douglas ex D. Don) forests. Fires then consumed surface fuels, thinned forest stands, and produced openings in the forest where shade-sensitive tree species could regenerate. Although historical fires were likely predominantly of low severity, the presence of extensive patches of montane shrubs in some areas indicates that stand-replacing fires of higher severity also occurred (Nagel and Taylor 2005).

Forests that developed under fire suppression after extensive logging in the Tahoe basin during the middle and later 1800s are now very different than those historical forests. Tree densities, particularly in smaller size classes, are now much higher, and species composition has shifted to favor firs over pines (Barbour et al. 2002, Taylor 2004). The abundance of trees and lack of fire return has led to unnaturally high amounts of surface fuels (Barbour et al. 2002), and greater fuel continuity, contributing to high fire hazard and greater probability of stand replacement upon burning (Manley et al. 2000, McKelvey et al. 1996, Skinner and Chang 1996).

Knowledge Gaps

Reducing surface and ladder fuels using prescribed fire or mechanical treatments has been shown to substantially improve the resilience of forest stands to wildfire (Agee and Skinner 2005, Pollet and Omi 2002); however, because of the importance of tourism, forest proximity to populated areas, and concerns about protection of natural resources, fuel management in the Lake Tahoe basin presents unique challenges. Smoke and liability issues may limit the use of prescribed burning in many areas. As a result, fuels in these areas are often treated mechanically or by hand, rather than through burning. Unfortunately, the extent to which mechanical forest treatments can mimic the ecological role of fire is poorly understood for many forest attributes (Weatherspoon and Skinner 2002). Because much of the excess forest biomass in the basin is in the form of small trees of low value, mechanical removal may not be cost-effective. As a result, new implementation strategies for reducing fire hazard, such as mechanical mastication or chipping, have been initiated. These methods leave the fuels on site, but alter their vertical profile, and have been shown not to result in soil compaction or erosion—yet concerns about fire effects such as soil heating, if the material should burn, remain (Busse et al. 2005, Hatchet et al. 2006; also see chapter 5, "Soil Conservation").

Even in areas where prescribed burning is a viable management option, smoke management and the narrow window available for prescribed burns in many years severely limit the number of acres that can be treated. Most fires in the Lake Tahoe basin historically occurred in the late summer or fall (Taylor 2004), and managers have often opted to conduct prescribed burns at that time of year; however, recent research has found that early-season prescribed burns, which typically consume less fuel, may have some benefits for at least the first burn in areas with heavy fuel loading (Knapp et al. 2005). Not only was the recovery of understory plant species more robust following early-season burns, but tree mortality was lower in early-season burns than late-season burns (Thies et al. 2005), although not significantly (Schwilk et al. 2006). Fire disturbance may also promote the invasion of exotic species (Keeley et al. 2003), and Merriam et al. (2006) and Kerns et al. (2006) reported a greater abundance of exotic plant species after late-season burns.

Forest fuels treatments can change forest habitat attributes required by many wildlife species, including vertical layering of vegetation, age structure of trees, tree composition, spatial distribution of remaining trees, snag and log densities and characteristics, and understory cover and species composition. The intensity and extent of fuels treatments and their objectives (i.e., only fuels reduction or some balance of ecological outcomes) can greatly differ among agencies and projects; thus, the magnitude of effects of treatments on plants and animals is directly related

Peter Goin

Prescribed pile burning as a means to reduce excess forest fuel loads. Tahoe Pines, Lake Tahoe basin.

to the intensity and extent of treatments. Treatments designed with fuel reduction as the primary objective tend to simplify and homogenize forest structure and composition. Further, they may extend impacts associated with urbanization farther into the forest by functionally extending edge effects. Simplified forest structure as observed in urban forest remnants (Heckmann et al. 2008) exhibited reduced biological diversity and ecosystem resilience (Manley et al. 2006; Sanford et al., in press; Schlesinger et al. 2008). Long-term environmental changes associated with fuel treatments are less certain, and will differ based on the combination of overstory treatments and postharvest treatments (chipping, pile and burn, prescribed burns) applied.

The impact of fuel treatments on plant and animal populations in the Tahoe basin is not known because of the general lack of information on the distribution and status of wildlife and plant populations in the basin, and the unique combinations of understory treatment (including chipping), large extent of actions, and rapid implementation of treatments being employed in the basin. Populations of many forest-associated species, particularly those associated with the montane zone, could be at risk of habitat fragmentation and isolation as a result of forest alterations.

These issues and uncertainties suggest the following broad management questions:

- What vegetation management approaches will be most effective and efficient in meeting a variety of management objectives, including reducing fire hazard, restoring forest health, increasing the amount and integrity of old-growth forests, maintaining and conserving biological diversity, and restoring a more natural fire regime?
- What locations are the highest priority for management and what balance of objectives are most appropriate in each location and throughout the basin?
- What measures are most informative and efficient in determining the effectiveness of vegetation management approaches in meeting fire and fuels management objectives?

Research Needs

Following are fire and fuels management research questions:

(**FR1**) How do current fuel treatments and future treatment scenarios simultaneously affect fire hazard and other values such as scenic and recreational amenity, water yield and quality, soil erosion, old-growth characteristics, and plant and animal diversity (including less-abundant species, narrowly distributed species, and forest and aquatic associates)? What are the effects of spatial distributions of fuel treatments on primary ecological management objectives in the basin, including (a) connectivity of populations of species expected to be most sensitive to changes in forest structure and understory conditions; and (b) maintaining quality habitat for aquatic species?

(FR2) Are there fuel treatment solutions that are optimal with respect to the multiple forest management objectives that exist in the basin (see question FR1), including considerations of cost? (This question could be addressed within a multiobjective modeling framework; the quality of the answers would depend at least in part on data from the kinds of field studies outlined below and elsewhere in this plan.)

(**FR3**) How do sensitive and vulnerable animal species associated with montane forests and aquatic inclusions (e.g., ponds and streams) use treated (masticated versus prescription-burned) and untreated areas to meet various needs (e.g., reproduction, foraging, movement, and shelter)?

(**FR4**) What are the projected consequences of current and projected fuel treatments for landscape connectivity for sensitive and vulnerable animal species?

(FR5) How does intensity of tree canopy thinning affect a range of ecosystem attributes? Is there a relationship between residual canopy cover after fuel treatments, and subsequent rates of surface and ladder fuel development? Do canopy openings and soil disturbance from fuel treatments favor establishment of shade-intolerant pine species? Is there a relationship between residual canopy cover and wildlife habitat value?

(FR6) How do alternative understory fuel treatments (e.g., canopy thinning followed by biomass removal, mastication and mulching, or prescribed burning) affect the trajectory of forest succession, including understory plant and animal species composition, relative abundances, and ecological community states and transitions? Do these treatments differ in resultant opportunities for invasive plant establishment? (It is recommended that the definition of forest succession include tree, shrub, herb, and grass plant forms, and that measurements include rate of fuel reaccumulation so that fire hazard can be calculated.)

(FR7) Mastication followed by mulching is a dominant mode of treatment of understory fuels currently used in the Lake Tahoe basin. Is the longevity of fire hazard reduction produced by mastication treatments related to vegetation type, resprouting potential, microenvironment, or chip depth? What are the ecological consequences of mulching compared to other treatment options? Will multiple cycles of treatment with mastication result in the buildup of unacceptably high amounts of surface fuels?

(FR8) How do alternative techniques for prescribed burning that are currently in use in the Lake Tahoe basin (jackpot, piling, understory, and piling with understory burns) compare in terms of fuel consumption and fire hazard, soil heterogeneity, wildlife responses, and wildlife habitat?

(FR9) What are the ecological consequences of season of treatment (early or late) when applying fuel treatments, such as mastication, mulching and prescribed burning? Important response variables might include mortality of remnant trees, resprouting of shrubs, and germination of species that have seed banks, and effects on small mammals and birds.

(FR10) What is the relative importance of ozone damage, soil depth, periodic drought, insect attack, and stand density in determining spatial patterns and temporal dynamics of tree mortality and subsequent surface fuel accumulation? What is the optimal range of temporal and spatial dynamics of tree mortality based on current and future climate conditions?

(FR11) What fuel treatments, if any, are most appropriate for the higher elevation forests in the Tahoe basin? What are the considerations for protecting against the spread or reducing the prevalence of root rot in red fir through fuel treatments?

(FR12) How effective are current fuel treatments in altering fire behavior, improving fire suppression effectiveness, and reducing fire severity, under the range of fire-weather conditions likely in the Lake Tahoe basin?

(**FR13**) What performance measures—including presence and abundance of plants and animals, forest structure and composition, and other biotic metrics—can be used to assess the effects and effectiveness of fuel treatment success at various times after treatment?

Special Communities Management

Biological diversity in the Lake Tahoe basin is a composite of species and the ecological communities of which they are members. Ecological communities that proportionally dominate the landscape typically are the primary focus of management. The Lake Tahoe basin, however, supports a number of classes or types of ecological communities that are limited in geographic extent but have great functional importance: among these are meadows, fens, aspen stands, riparian areas, and lakeshore marsh and beach communities.

These communities support disproportionately large numbers and a high diversity of animal and plant species, and some serve as nodes linking upland ecosystems and Lake Tahoe. Each community has particular threats to its integrity. Ecological communities and species with high conservation value are addressed individually, including their status and the composite of potential effects of management activities.

Aspen

Quaking aspen (*Populus tremuloides* Michx.) occurs in the Lake Tahoe basin in riparian areas, bordering meadows, as stand-alone groves in snow pockets or avalanche paths, or as disjunct patches interspersed with conifer forest (Shepperd et al. 2006). Aspen stands support high plant diversity relative to surrounding vegetation (Potter 1998), and use less water than conifer forests of equivalent area (Gifford et al. 1984). Many authors contend that in the semiarid West, aspen is second only to riparian habitats themselves in terms of the biodiversity they support and in importance as wildlife habitat. Aspen stands typically support a greater diversity and abundance of birds, mammals, and invertebrates than adjacent vegetation types (DeByle 1985, Flack 1976, Salt 1957, Schimpf and MacMahon

1985). For example, several bird species have a strong affinity with aspen, including northern goshawk, red-naped and red-breasted sapsuckers (*Sphyrapicus nuchalis/ruber*), dusky flycatcher (*Empidonax oberholseri*), warbling vireo (*Vireo gilvus*), Swainson's thrush (*Catharus ustulatus*), and MacGillivray's warbler (*Oporornis tolmiei*) (Finch and Reynolds 1988, Flack 1976, Heath and Ballard 2003, Richardson and Heath 2004, Salt 1957). Several mammal species also show affinities for aspen, including ungulates such as mule deer (*Odocoileus hemionus*), rodents such as pocket gophers (*Thomomys*), voles (*Microtus*), shrews (*Sorex*), and mountain beaver (*Aplodontia rufa*) (Beier 1989, Coggins and Conover 2005, Loft et al. 1991). The invertebrate communities associated with aspen in the Sierra Nevada are not well studied, but in Rocky Mountain National Park, 33 of 49 resident butterfly species were found in aspen, and 7 of those were unique to aspen forests (Chong et al. 2001).

Knowledge Gaps

In the absence of disturbance by fire, conifers have heavily encroached upon most aspen stands in the Lake Tahoe basin. Encroachment of conifers into aspen stands can have negative impacts on herbaceous cover, stand moisture, and invertebrate, mammal, and bird species richness and abundance. Many species of plants, birds, mammals, and invertebrates benefit from the thick herbaceous layer and deep leaf litter typical of aspen stands that experience periodic disturbance. In a recent inventory and assessment effort by the U.S. Forest Service, approximately 68 percent of aspen stands were designated as being at moderate to extremely high risk of extirpation (Shepperd et al. 2006). Restoration of decadent aspen stands elsewhere in the northern Sierra Nevada has met with considerable success (Jones et al. 2005). Information on the value of aspen in supporting animal populations in the Tahoe basin is still limited, but the few local studies that have been conducted suggest healthy herbaceous communities and limited conifer intrusion may be the optimal habitat condition for at least aspen-associated breeding birds (Richardson 2007, Richardson and Heath 2004). Clearly, approaches to managing aspen in the basin will directly affect many plant and animal species.

These issues and uncertainties suggest the following broad management questions:

- Where and to what ecological condition should aspen stands be restored in the Lake Tahoe basin?
- What is the desirable extent, configuration, and distribution of aspen stands (patches) that will assure ecological benefits to wildlife and co-occurring vegetation?

- What management actions can contribute to restoring and sustaining aspen stands in the Lake Tahoe basin?

Research Needs

Following are aspen research questions:

(**A1**) How well can we map and predict aspen existence from currently available methods (e.g., satellite imagery)? How well can stand condition be assessed with these methods, compared with ground surveys? What variables best predict the occurrence of plants of concern (e.g., physiographic, woody debris, indicator species, soil types, hydrologic regimes)?

(A2) What was the historical versus the current ecological status of aspen communities and associated plant and animal populations? How have these communities changed in the absence of periodic disturbance from fire? What stand attributes (e.g., stand area, species composition) are critical to maintaining populations of the most closely associated species?

(**A3**) What management tools and actions can be identified that will best facilitate conversion of conifer forest to desired aspen conditions?

(**A4**) How does aspen restoration affect associated plant and animal populations, and ecological communities? Are species and communities responding to restoration efforts as expected?

(**A5**) What performance measures—including presence and abundance of plants and animals and other ecological metrics—can be used to assess treatment effects and effectiveness in restoring aspen biological diversity and ecological function and monitoring conditions over time?

Riparian Areas

Riparian areas support high diversities of plant and animal species owing to the presence of water, diverse vegetation composition and structure, and abundant food resources. Many riparian areas in the Lake Tahoe basin were degraded from overuse in the late 1800s, but current problems stem largely from lack of fire combined with the legacy of historical channel alterations.

Knowledge Gaps

Riparian areas have been mostly excluded from forest fuel treatments because of concerns about soil disturbance resulting in nutrient and sediment deposition into streams and ultimately into Lake Tahoe. The limited management activity in proximity to stream riparian areas (also known as Stream Environment Zones or


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Riparian habitat along the Upper Truckee River, Lake Tahoe basin.

SEZs) has resulted in the invasion of shade-tolerant conifers into many riparian areas. Conifers are thought to compete strongly with riparian vegetation (Haugo and Halpern 2007, Jones et al. 2005, Lang and Halpern 2007, Stam et al. 2008). Consequences of the lack of fire in riparian habitats include a greater density of small-diameter trees and an overabundance of small woody debris in some areas. There are concerns that altered conditions in riparian areas translate into higher risk of high-intensity fire in these areas, substantially increasing sedimentation and nutrient inputs to Lake Tahoe. There also is potential for fire from lower elevations to expand into higher elevations via riparian corridors despite aggressive upland fuel treatment efforts. In addition, one special status species—the mountain beaver—is most closely associated with riparian areas, so riparian management is likely to directly affect the mountain beaver. The lack of information on the historical and current status of riparian ecosystems, including the status of associated plant and animal species, impedes determination of the ecological characteristics of natural community recovery, desired conditions, and opportunities for habitat and stream restoration. Management in these zones could be carried out with greater confidence if more information existed regarding historical vegetation structure and composition, and riparian area disturbance regimes.

These issues and uncertainties suggest the following management questions:

- What is the extent and condition of riparian ecosystems in the Lake Tahoe basin, and what conditions should management attempt to create through available techniques, including the use of fire?
- What measures are most informative and efficient in determining the condition of riparian ecosystems and their potential responses to management and environmental factors?

Research Needs

Following are riparian research questions:

(**R1**) How well can we map riparian vegetation using currently available methods (e.g., satellite imagery), and what is the current location, extent, and condition of riparian vegetation in the basin based on these methods? How effectively can riparian condition be assessed using these methods, compared with ground surveys? What variables best predict the occurrence of plants of concern (e.g., physiographic variables, woody debris, indicator species, soil types, or hydrologic regimes)?

(**R2**) What was the historical versus the current ecological status of riparian plant and animal communities in the basin? What was the historical role of fire frequency and intensity in shaping riparian-area composition and structure in the basin? What was the historical composition and structure of vegetation in riparian areas, including the density of standing and downed woody debris?

(R3) Are riparian systems recovering naturally from historical anthropogenic disturbances? The need exists for a system to objectively classify riparian vegetation and its condition, compile and assess stream and wetland restoration efforts in the basin, review the efficacy of stream and wetland restoration techniques that are in use, and develop a system for assessing success of riparian restoration projects.

(R4) Does stream restoration have desired effects on riparian habitat and associated plant and animal species? How does restoration involving fire or fuel treatments differentially affect species richness or abundance?

(R5) What is the distribution and abundance of the mountain beaver population in the Tahoe basin, with what habitat features are they most closely associated, and how can their populations be most efficiently monitored?

(**R6**) What performance measures—including presence and abundance of plants and animals and other ecological metrics—can be used to assess treatment effects and effectiveness in maintaining, restoring, and rehabilitating riparian biological diversity and ecological function, and to monitor conditions over time?

Fens and Meadows

Fen and wet meadow communities are tightly linked to water-table attributes (Allen-Diaz 1991, Castelli et al. 2000, Kluse and Allen-Diaz 2005) and soil water chemistry (Atekwana and Richardson 2004, Bartholome et al. 1990). Many species of plants and some animal species, such as butterflies, fossorial mammals (e.g., gophers, moles, and marmots), meadow nesting bird species (e.g., willow flycatcher [*Empidonax traillii*] and mountain bluebird [*Sialia currucoides*]), and soil macro-invertebrates, are restricted to fens or meadows, which themselves are susceptible to impacts from human activities in the Lake Tahoe basin.

Knowledge Gaps

Past land uses, including grazing and water diversions, have resulted in degraded resource conditions. Approximately half of the basin's meadows have been permanently lost, fragmented, or altered in critical physical and biotic characteristics owing to these disturbances (Cobourn 2006, Elliot-Fisk et al. 1997). Grazing is no longer prevalent in meadows in the Lake Tahoe basin, but there may be substantial legacies of this former major land use (particularly altered plant and animal species composition), similar to circumstances elsewhere in the Sierra Nevada (Dull 1999).

Meadows and fens also suffer current impacts primarily from recreation activities, which can result in soil compaction, desiccation owing to incision of streambeds, and conifer encroachment (Martin and Chambers 2004). Recreational activities in meadows primarily consist of hiking, biking, cross-country skiing, and snowmobiling, with some motorcycle and all-terrain vehicle (ATV) activity. These activities can have both direct and indirect negative impacts on plants and animals. Hiking, mountain biking, and off highway vehicle (OHV) use leads to proliferation of trails in heavily used areas, causing fragmentation and soil compaction and erosion. Trail use also disturbs many wildlife species, leading to increased stress or decreased foraging time, which may have negative consequences for survival and reproduction. Snowmobile use is prevalent in meadows during the winter (and on established routes through the forest). Snowmobile use compacts the layer of snow close to the ground where small mammals, particularly voles, move during winter, and commonly damages vegetation. Mammalian carnivores and raptors (including bobcat [*Lynx rufus*], northern goshawk, and bald eagle) tend to be sensitive to vehicle use, but also may use compacted snow for travel, changing the spatial pattern of their movements and predation. Preliminary results from recent research suggest summer and winter OHV use does not affect the probability of use of an area by marten, a species of concern in the Tahoe basin (Zielinski and Slauson 2008).

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Meadow-stream complex, Angora Creek, Tahoe Paradise, Lake Tahoe basin.

Although we have a basic understanding of general cause-effect relationships between recreation and plant and animal responses, the information is not specific enough to inform the development of management thresholds. It is not clear which species are most impacted by recreation, the ecological and social consequences of those impacts in the basin, and how growing numbers of visitors may exacerbate those effects. Two special-status species are closely associated with fens and meadows: mountain yellow-legged frog (*Rana muscosa*) and willow flycatcher. The only robust population of mountain yellow-legged frogs in the basin is located in a fen (see "Special Communities" for more details).

Stream restoration may reverse some losses of meadow habitat, and reconfigurations of channels may allow streams to meander more, and carry water to a greater area. Similarly, where some streams meet roads, they have historically been forced through a single culvert; planned additional culverts will increase the area "watered" by a stream (e.g., at Blackwood Creek). These restoration efforts may expand meadow habitat; influences on these populations could be detected by monitoring before and after restoration.

These issues and uncertainties suggest the following management questions:

- Where are the Tahoe basin's fens and meadows located, and what are their current conditions?
- What management actions can contribute to restoring and sustaining fens and meadows in the basin?
- What measures are appropriate to assess the condition of fens and meadows and efficacy of management actions?

Research Needs

Following are fens and meadows research questions:

(**FM1**) Where are fens and meadows located in the Tahoe basin, and what are their current ecological characteristics and conditions? How important is water chemistry and ground-water hydrology in establishing and maintaining fen conditions?

(**FM2**) What are appropriate reference conditions and historical conditions for fens and meadows in the Lake Tahoe basin?

(FM3) How do current and potential future management and restoration practices in fens and wet meadows, including application of fire or fire surrogates, affect their susceptibility to invasion by unwanted plant species?

(FM4) How well do predictive models of meadow recovery, with and without restoration, apply to the Lake Tahoe basin circumstances? Which meadows should be used to validate these models, and what data need to be collected? How should meadows be assigned in a priority scheme for restoration?

(**FM5**) How are fens and meadows impacted by current disturbances, including water use, fire suppression, recreation, and beaver activities? Which meadows are most critical to maintaining populations of meadow-dependent species in the basin?

(FM6) To what extent do recreation-associated impacts (both direct and indirect) in meadows change composition, abundance, and behavior of wildlife species? Do some species seasonally avoid meadow and riparian habitat because of snowmobiles, bike or foot traffic, or dogs?

(**FM7**) What performance measures—including presence and abundance of plants and animals and other ecological metrics—can be used to assess conditions, assess the effects and effectiveness of efforts to restore or rehabilitate meadow biological diversity and ecological function, and monitor conditions over time?

Lakeside Marsh and Beach Habitats

Marsh and beach habitats in the Lake Tahoe basin are limited in number and extent. The largest marshes occur in the southern part of the basin in association with the mouth of Upper Truckee River, Trout Creek, and Tallac Creek. Marshes provide the only suitable habitat for a large number of species in the basin, including many species of waterbirds (Manley et al. 2000). Beaches are numerous around Lake Tahoe, but they are limited in extent, particularly in years of high lake levels.

Knowledge Gaps

Lakeside marsh and beach habitats have had their historical hydroperiods altered by the damming of the lake's outlet. This has had adverse effects on Tahoe yellow cress (*Rorippa subumbellata* Rollins) (Pavlik and Murphy 2002), caused changes in marsh plant communities (Kim and Rejmankova 2001), hindered recent attempts to restore marsh habitat destroyed by lakeside housing developments,[7] reduced populations of waterbirds, and may have fostered encroachment by lodgepole pine (*Pinus contorta* Douglas ex Louden) into lakeside areas.

Tahoe yellow cress is a low-growing, perennial species endemic to the shores of Lake Tahoe. The species is listed as endangered by both states, is considered endangered or threatened by the California and Nevada Native Plant Societies, and is a candidate species for listing under the Endangered Species Act. The species has been the focus of a conservation strategy for the past 4 years, with the goal of restoring a self-sustaining metapopulation. Lack of access to certain privately held lakeshore areas has made it difficult to know whether this goal is being achieved. Additional uncertainty comes from lack of knowledge of seed bank dynamics, seed and rootstock longevity and dispersal, and genetic relationships among core and satellite populations.

[7] Hunter, J. 2008. Personal communication. Senior ecologist, EDAW, Inc., 870 Emerald Bay Rd., South Lake Tahoe, CA 96150.

Peter Goin

Dairy Meadows in autumn, Taylor Creek watershed, South Lake Tahoe, California.

Waterbirds (including ducks, shorebirds, and rails) are special-status species that find their primary habitat in lakeside marshes. Their populations have fallen in response to the loss of much of Pope Marsh to development in the 1960s (Manley et al. 2000). The TRPA has conducted surveys of key marshes around the lake for the past 7 years, and their findings are summarized in the Pathway planning documents.[8]

These issues and uncertainties suggest the following management questions:

- What management actions will contribute to restoring and sustaining desired ecological values and biodiversity in Lake Tahoe's lakeside marsh and beach habitats?
- What ecosystem attributes should be subjected to monitoring to assess the effectiveness of management actions directed at lakeside marsh and beach habitats?

Research Needs

Following are lakeside, beach, and marsh research questions:

(**LM1**) For shoreline plants of concern, does the spatial extent of existing populations support life-history requirements (including access to pollinators, disturbance regimes, seed dispersal)? What environmental factors most affect the persistence,

[8] Kelchlin, E. 2007. Personal communication. Wildlife biologist, Tahoe Regional Planning Agency, 128 Market Street, Stateline, NV 89449.

extent, and reproductive success of populations at a given site? Are there genetic strains of shoreline plants that are more robust to environmental stressors, thus conferring enhanced survival?

(**LM2**) What is the ecological status of marsh habitats in the basin, and what measures can be taken to retain and restore their ecological integrity?

(LM3) What performance measures—including presence and abundance of plants and animals and other ecological metrics—can be used to assess treatment effects and effectiveness in maintaining, restoring, and rehabilitating the biological diversity and ecological function, and to monitor conditions in marsh and beach habitats?

Aquatic Ecosystem Restoration

The ecology of the aquatic ecosystems within the Lake Tahoe watershed has been altered dramatically over the last two centuries. Most of our knowledge of historical change has focused on alterations to Lake Tahoe itself; however, lakes, streams, and meadows within the upper watershed also have been altered resulting in the increased need to manage these ecosystems. In this section, we differentiate Lake Tahoe and other aquatic ecosystems to assist in interpreting the change and research needs for these distinctive ecosystems. We focus specifically on alterations from eutrophication, potential changes owing to atmospheric loading of nitrogen, and the influence of nonnative species (plant and animal) on the restoration or management of native biota.

Lake Tahoe

Prior to large changes in community structure and conditions of nutrient loading brought about by human activities, Lake Tahoe's community assemblage was relatively simple with 12 orders of zoobenthic taxa, 6 zooplankton species, and 8 fish taxa (Chandra 2003, Frantz and Cordone 1996, Juday 1906, Miller 1951, and Vander Zanden et al. 2003). The benthic invertebrate community supported one endemic, wingless form of stonefly. Beginning in the mid to late 1800s, species introductions combined with landscape disturbances started to alter the lake's biology.

The preinvasion food web (circa 1872) was dominated by a single predator, Lahontan cutthroat trout (*Oncorhynchus clarki,* subspecies *henshawi*), which fed primarily on pelagic tui chub (*Siphateles bicolor pectinifer*) and zooplankton (Chandra 2003, Juday 1906, Vander Zanden et al. 2003). Forage fishes obtained energy from a mix of benthic and pelagic primary production sources. By 1939, cutthroat trout were extirpated from Lake Tahoe, and a lake trout (*Salvelinus namaycush*) population replaced them as the top predator (Cordone and Frantz

1966). Three primary reasons for the demise of cutthroat trout were predation from introduced lake trout, the degradation of spawning stream habitat from increased siltation owing to watershed deforestation (Moyle 2002), and the hybridization of cutthroat trout with rainbow trout owing to hatchery propagation.[9] There have been several attempts to reestablish both fluvial (stream form) and lacustrine (lake form) cutthroat populations in the Tahoe basin, all of which failed. As part of the U.S. Fish and Wildlife Service recovery plan for cutthroat trout (Coffin and Cowan 1995) in its native range, efforts have begun to restore cutthroat in Fallen Leaf Lake, located in the southern end of the basin.

Crayfish (*Pacifastacus leniusculus*) were introduced multiple times into Lake Tahoe and were established by 1936; they are now found in large numbers (55 million in the late 1960s and 230 million by early 2000 (Abrahamsson and Goldman 1970, Chandra and Allen 2001). Studies suggest that, under low densities (0.16 adult/m^2), the crayfish stimulate periphyton productivity by removing old senescent cells (Flint 1975). Today, crayfish do not contribute to the energetics of nonnative lake trout except for the largest size classes (>50 cm).

Chandra et al. (2005) investigated the effects of cultural eutrophication on the coupling between pelagic primary producers and benthic consumers in Lake Tahoe. At depths where ambient light levels equal 1 percent (which have shifted with time from 50 to 85 m), pelagic primary producer and zoobenthic consumer coupling was positive. Historically, the zoobenthos from this depth zone obtained 32 percent of their energy from phytoplankton sources; after 43 years of eutrophication, they obtained 62 percent of their energy from those sources. A simple model indicated increased pelagic production and resultant export of matter, combined with the loss of benthic primary production, has contributed to the change in zoobenthos energetics. Recent samplings of zoobenthos during 2008–09 suggest there may be a 50 to 80 percent loss in benthic invertebrate density and biomass in Lake Tahoe. Furthermore, there has been a substantial decrease in the density of native, endemic invertebrates such as the blind amphipod and more cosmopolitan invertebrates such as oligochaete worms (Chandra and Caires 2001). Whether this loss is due to a shift in pelagic to benthic coupling or from alterations to Mysid shrimp is unclear (see below).

The establishment of the invertebrate *Mysis relicta*, corresponded with shifts in the trophic niches of forage fishes (chubs) and the top predator lake trout, and a feeding shift of lake trout to pelagic energy sources. The resultant increase in lake trout may have increased predation rates on native forage fishes and decreased

[9] Cordone, A.J. 2007. Personal communication. Fisheries biologist, retired. California Department of Fish and Game, 1416 Ninth Street, Sacramento, CA 95814.

their abundance (Vander Zanden et al. 2003). Growth rates of lake trout before and after mysid introduction do not appear to have changed, except in the smaller size classes. Post *Mysis* invasion studies in Lake Tahoe showed impacts on other biological components of the lake. A strong restructuring of the zooplankton community as a result of *Mysis* predation on native cladocerans occurred, shifting the lake's pelagic environment to a *Mysis* and copepod-dominated system. Furthermore, modeling and empirical measurements suggest mysids may be influencing the carbon dynamics at the sediment-water interface as they feed in the deep part of the lake during the daytime and resuspend sediment particles through excretion during the nighttime as they migrate to the pelagic zone (Chandra 2003). Thus the insertion of *Mysis* into the middle of the food web played a strong determining role in restructuring upper trophic level energetics, and in disrupting community dynamics in the middle and lower parts of the food web. Their role and impact at lower depths is unclear; however they may be playing a role in disrupting carbon dynamics in the deepwater and pumping particles back into the water column.

In the mid to late 1970s, and again in the late 1980s, a variety of nonnative species were discovered in the near-shore environment, primarily driven by the establishment and expansion of nonnative aquatic plants, which provided habitat and refugia for nonnative fishes. The warm-water fish introductions were illegal and thought to be the result of anglers eager to catch these fish. During that period, in the Tahoe Keys, a major rearing area of native fishes, warm-water fish species were rarely found, whereas native minnows remained abundant as evidenced by a snapshot sample obtained in 1999; however, by 2003, largemouth bass (*Micropterus salmoides*) were common, whereas redside shiner (*Richardsonius balteatus*) and speckled dace (*Rhinichthys osculus*) populations declined or were virtually eliminated from the Tahoe Keys (Chandra 2009, Kamerath 2009). The change in fish structure was substantiated by fishing guides operating out of the Tahoe Keys: within a decade they could no longer collect the minnows that were commonly used as bait by fishing charters on the lake.

Until 1994, no lakewide surveys for rooted aquatic macrophytes had been conducted in efforts to document the presence of nonnative species. Early reports (1975) of water milfoil species near Taylor Creek did not identify the species of *Myriophyllum*, nor were vouchers or photographic records made. However, severe impacts from aquatic plants were observed in the Tahoe Keys by the end of the 1970s and early 1980s, during which time mechanical harvesting was begun. Recent studies have documented the role of some of the invasion pathways and vectors (boats and boat trailers) for aquatic plants that are transported both to and away from Lake Tahoe (Wittmann 2008). These vectors contribute to issues of continued reinfestation and potential new infestations of nonnative aquatic plant species.

In 2008, established populations of the nonnative bivalve species, the Asian clam (*Corbicula fluminea*), were discovered in the southeastern portion of Lake Tahoe by University of California, Davis researchers during regular near-shore periphyton surveys. Asian clams were first detected in Lake Tahoe in very low numbers at Timber Cove in 2002 (3 to 20 clams/m^2—Hackley et al. 2008), and at Nevada Beach in 2003.[10] Extensive field surveys during summer 2008 revealed much higher densities of Asian clams (50 to 3,000 clams/m^2), suggesting evidence for local population growth and possible reintroduction from external populations. Asian clams in Lake Tahoe compete with other local native molluscan species, such as the montane pea clam (*Pisidium* spp.) and the ramshorn snail (Planorbidae). Its current known distribution (area ~1 million m^2) is patchy along the southeast shore of the lake from Zephyr Cove to El Dorado Beach, and is rapidly expanding and colonizing a variety of physical circumstances.

Knowledge Gaps

Lake Tahoe's ecological community has changed through the elimination of native trout, restructuring of food web energy flow, and introduction of species that occur in both the limnetic and littoral zones. It is unclear, however, how some of these introduced species are impacting near-shore and offshore water quality as well as native fish biomass and production. In addition, three special status species are primary participants in the Lake Tahoe food web—Lahonton cutthroat trout, osprey (*Pandion haliaetus*) and bald eagle. Populations of osprey and bald eagle are likely to be affected by changes in the relative and absolute abundance of fishes in Lake Tahoe.

Mysis shrimp are the lake's dominant macrozooplankton, exhibiting a large (up to 400 m) diel vertical migration to the lake bottom (Rybock 1978). While on the bottom, mysids feed on sediment detritus and may actively pump detritus and nutrients into the lake's limnetic zone (Chandra 2003). Research from other ecosystems suggesting mysids are supported by benthic detrital energy sources is supported by a number of studies (Lasenby and Lanford 1973, Lasenby and Vanduyn 1992, Lester and Mcintosh 1994, Song and Breslin 1999, Viherluoto et al. 2000). Many ecotoxicological studies have determined that *Mysis* ingest heavy metals and organochlorines directly from sediment (Lasenby and Vanduyn 1992, Lester

[10] Herbst, D. 2003. Personal communication. Aquatic invertebrate ecologist, University of California Sierra Nevada Aquatic Research Laboratory, HCR 79, P.O. Box 198, Mammoth Lakes, CA 93546.

and Mcintosh 1994, Song and Breslin 1999), and serve as a vector for contaminant transport to the pelagic zone. Gut content information also suggests mysids may derive a substantial amount of their energy from benthic resources, including zoobenthos and organic-rich sediment particles (Lasenby and Lanford 1973).

The effect of warm-water invasive species on the native fish community and the potential for recycling nutrients in the near-shore habitat are important uncertainties. Recent surveys suggest warm-water fish such as bass (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*), and catfish (*Ameiurus nebulosus*) are found around the lake. Recent assessment of their distribution indicated the densities are still very low compared to other ecosystems and can be variable over time. Overall the densities were low around most of the lake with higher densities in some locations such as Meek's Marina and intermediate densities in the Tahoe Keys. Anecdotal observations indicated that bass may be in open water areas of the lake; however, it is unclear the extent to which bass have established in these areas or if they were moving through migration zones before they reach more enclosed sites such as marinas and embayments (Chandra et al. 2009). Although preliminary research suggests these fish are competing and/or preying upon native fishes in the near shore (Kamerath 2009), the role that nonnative crayfish and other physical factors may play in controlling warmwater fish establishment as well as recruitment around the lake remains unclear. Crayfish are a preferred food source for bass in their native habitats. Currently, the invasive crayfish in Lake Tahoe seem to have expanded in population since estimates were first made in the 1970s, with over 230 million individuals in the lake estimated in 2001 (Chandra and Allen 2001). Current models that predict warmwater fish distribution (Chandra et al. 2009, Kamerath 2009) do not account for crayfish as a food resource in the lake and how they may contribute to bass growth and maintenance. Furthermore, using Lake Tahoe fishes researchers have found that ultraviolet light penetration may control recruitment of nonnative fishes and allow the persistence of native fishes.[11] Thus, there may be direct ties between the lake's clarity and the distribution of warmwater fishes. These two resource controls of food availability and physical light constrains should be incorporated into existing models predicting warmwater fish establishment in the lake to refine areas for monitoring as well as management.

The recent invasion of the near-shore area by warm-water species such as bass species could lead to the remobilization of nutrients in this habitat. Examination of seasonal nutrient availability is recommended, particularly during low flow periods, to determine the biological contribution of nutrients to near-shore

[11] Williamson, C. 2009. Personal communication. Professor in ecology, Miami University, Department of Zoology, Pearson Hall 158, Oxford, OH 45056.

production and lake clarity. The interactions between native and nonnative plants also are poorly understood. With the continued expansion of Eurasian water milfoil (*Myriophyllum spicatum*), and the newly expanded populations of curly leaf pondweed (*Potamogeton crispus*), the uncertainties of fish/plant interactions are even more complex.

Eutrophication of Lake Tahoe has led to a shift in energy flowing to the bottom of the lake (Chandra et al. 2005). It is unclear, however, if increased coupling between pelagic to benthic energy flows along with carbon alteration due to *mysid* shrimp are altering benthic invertebrate community structure and production—an issue of particular importance when trying to manage native, benthic biodiversity such as the endemic, wingless stonefly (*Capnia lacustra*) or blind amphipod (*Stygobromus* sp.) and in evaluating the potential for the reintroduction of native species.

Environmental impacts resulting from Asian clam establishment in Lake Tahoe related to water quality, benthic community structure and production, and the potential for the facilitation of invasion of other near-shore invasive species through habitat disturbance and localized increases in nutrient concentrations are uncertain. In particular, the Asian clam (1) excretes elevated levels of nitrogen and phosphorus into the water column and sediment substrate (Wittmann et al. 2008)—which can promote increased algal growth; (2) is able to filter extremely high volumes of water (Vaughn and Hakenkamp 2001)—potentially impacting both water quality and pelagic communities including Lake Tahoe sports fisheries; and (3) can increase levels of calcium through the concentration of dead shell matter—providing potential substrate and appropriate biochemical conditions for the establishment of other nonnative bivalve species such as the quagga (*Dreissena rostriformis bugensis*) and zebra mussel (*Dreissena polymorpha*). Current knowledge about the Asian clam in Lake Tahoe is limited because of the short time since its discovery. Continued efforts to assess the life history, environmental impact, and distribution, and to identify possible control and management actions in Lake Tahoe are underway.

Finally, little is known about the ecology and nutrient dynamics of Emerald Bay. This bay is an important destination for recreational boaters from various parts of the lake and particularly the Tahoe Keys, where most of Lake Tahoe's nonnative species issues currently reside. At least 8 nonnative species have been observed in Emerald Bay including but not limited to Eurasion watermilfoil, largemouth bass, catfish, Mysid shrimp, lake trout, crayfish, Asian clam, and kokanee salmon. Efforts to integrate and assess the limnology and food web ecology of this bay are recommended as it is likely that future invaders will establish in this location owing to the amount of propagule pressure occurring through boat traffic,

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Kokanee spawning, Taylor Creek, South Lake Tahoe.

warmer temperatures, and increased productivity. Furthermore, due to its isolated nature and increased productivity compared with Lake Tahoe, this may be an important area for restoring the native Lahontan cutthroat trout.

These issues and uncertainties suggest the following key management questions:

- What management actions are necessary to restore and sustain a desired food web in Lake Tahoe, and will those actions be consistent with efforts to reverse declines in the lake's clarity?
- What are the appropriate measures of management and restoration program actions to assess their effectiveness in meeting ecosystem objectives?

Research Needs

Following are Lake Tahoe aquatic ecosystem research questions:

(**LT1**) What is the interaction between nonnative and native species in the basin, and how does this affect our ability to manage native biodiversity?

(LT2) What is the linkage between habitats (i.e., profundal-pelagic, littoral-pelagic) for carbon, phosphorus, and sediment transport particularly with the introduction of nonnative species? How does this affect Lake Tahoe water quality and clarity and native benthic invertebrate biodiversity?

(LT3) What is the seasonal role of mysid shrimp in controlling native plankton and benthic invertebrate populations and reducing water clarity through the transport of benthic nutrients and sediment particles into the water column? Ideally, research would focus on understanding the life cycle, contemporary feeding behavior, and the role mysid shrimp may play in reducing water clarity in Lake Tahoe.

(LT4) Can we predict future invaders (plant or animal) and the potential impacts to the lake's water clarity or biodiversity?

(LT5) Will current limnological characteristics support the establishment of non-native species or the potential recovery of native fish populations in Emerald Bay?

(**LT6**) What is the variability of benthic algal production and does this affect near-shore production and clarity? Will nonnative species alter this production? Future research is recommended to examine the production of benthic algae and invertebrates such as invasive crayfish to determine if eutrophication is affecting ecological community structure.

(LT7) What is the status of osprey and bald eagle populations in the basin, and how do their distribution, abundance, and productivity track changes in fish populations in Lake Tahoe?

(LT8) How can we best ensure the survival of native fish and other desired aquatic vertebrates? What stressors are affecting native species, and what can be done to lessen negative impacts?

(**LT9**) How can we restore native fishes and other aquatic vertebrates to the lake? What portions of Lake Tahoe are best suited to reintroduction efforts for native species? How will established nonnative species likely affect the success of restoration efforts?

(LT10) How can water quality and water clarity be protected from the effects of introduced species and human activities? What aspects of water quality and clarity are at most risk? What management actions might contribute to minimizing negative impacts from those sources?

(**LT11**) What is the current distribution of the Asian clam in Lake Tahoe, and what are its ecosystem-level impacts? How does it impact near-shore quality and the potential facilitation of the invasion of other nonnative aquatic species?

Other Aquatic Ecosystems in the Lake Tahoe Basin

Much of the research carried out in the Lake Tahoe basin has focused on understanding the impacts of watershed development, nutrient loading, water quality, and aquatic ecology in Lake Tahoe itself. Very little effort has been placed on evaluating the response of other lakes, streams, and other aquatic habitat types to the array of human disturbances affecting them, including ground disturbance, increased inputs from atmospheric pollution, and the impacts of nonnative species (fish, amphibians, plants) introductions.

The aquatic ecosystems research that has been conducted has been short term (seasonal or one-time assessments), primarily owing to funding constraints. For example, Marlette, Cascade, Fallen Leaf, Echo, and Spooner Lakes all have been evaluated for one or all of the following constituents: nutrient status (e.g., phosphorus, and nitrogen), basic physical and chemical measurements (e.g., dissolved oxygen, temperature, and pH), pelagic primary production, and zooplankton composition and biomass (e.g., Lico 2004, Reuter et al. 1996; University of California, Davis and University of Nevada, Reno 2003, 2006). In 2006, an effort was made to assess the nutrient concentrations via depth profiles and limitation (nitrogen, phosphorus, or co-limitation) for Upper and Lower Echo, Upper and Lower Angora, Fallen Leaf, Tahoe, Eagle, Spooner, and Marlette Lakes. Results showed the pelagic primary production in five lakes (Tahoe, Marlette, Fallen Leaf, Lower Echo, Lower Angora) was co-limited; Spooner Lake exhibited possible nitrogen limitation, and data from Eagle Lake were inconclusive (Chandra and Rost 2008).

Other research has focused on the ecology of some of the small lakes in the Tahoe basin. For example, Cascade Lake has a biological assemblage that closely resembles that of Lake Tahoe prior to the introduction of the two nonnative species (*Mysis relicta* and lake trout, *Salvelinus namaycush*). Vander Zanden et al. (2003) presented a food web structure for this lake in 2001, finding that hybridized cutthroat trout are a dominant predator feeding on pelagic energy sources (e.g., zooplankton). Since 2001, researchers from the Universities of California-Davis, Nevada-Reno, Wisconsin-Madison have been monitoring the biology and general limnology (nutrients, chlorophyll a) during spring, summer, and fall in Fallen Leaf Lake. This lake experienced the reintroduction of native Lahontan cutthroat trout (information on the bioenergetics, historical changes to the lake's fishery, and limnology can be found in Allen et al. 2006). The California Fish and Game and U.S. Forest Service have also attempted to control nonnative brook trout populations on an annual basis to promote the persistence of cutthroat trout in the Upper Truckee River and Meiss Meadows watershed. This effort of more than 10 years has promoted the recovery of native trout; however, the effect of removal of book trout on life history characteristics of cutthroat trout (including growth, survival, and condition) has not been evaluated on a regular basis. Limited food web and genetic information has been obtained for Stony Ridge and Gilmore Lakes.

Most amphibian species in the basin are primarily associated with standing water bodies. Pacific treefrog (*Hyla regilla*), long-toed salamander (*Ambystoma macrodactyla*), and western toad (*Bufo boreas*) are all primarily associated with standing water, although the two frogs are also found in streams. Stocking non-native fish creates large populations of predators that prey on larval amphibians. The U.S. Forest Service has conducted surveys of lakes throughout the watershed to determine the presence of fishes, amphibians, snakes, and waterbirds over the last decade. The limited distribution of most amphibian species has led to an analysis of genetic diversity by University of California, Davis, University of Nevada, Reno and U.S. Forest Service researchers[12] of three species: long-toed salamander, western toad, and mountain yellow-legged frog. These data are being analyzed to better inform restoration efforts and promote amphibian populations that have been shown to be in decline in the Sierra Nevada.

Based on research to date in and near the Lake Tahoe basin, nonnative trout are likely to be a primary factor limiting the distribution and population size of native amphibians there (Knapp and Matthews 2000, Manley and Lind 2005). Although fish stocking has been discontinued on the California side of the basin, it continues on the Nevada side. Some streams in the California side of the basin have been designated "Wild Trout Areas" and are not (officially) stocked with nonnative fishes. It is not clear to what degree this management response benefits amphibians and stream-associated reptiles. Studies in the Sierra Nevada have shown that, without intervention, decades are required for trout populations to decline once stocking has ceased (see Knapp et al. 2001). Fish stocking could potentially benefit garter snake populations, as they can prey on fry. Bullfrogs (*Lithobates catesbeianus*) are also a potential threat to amphibian populations in the basin; however, they currently have a limited distribution, primarily in the mouths of streams in the southern basin. The number of sites occupied is fairly low, but where they exist, their populations are large and affect the native fauna (Manley and Lind 2005).

Stream channel restoration is an active pursuit in the Lake Tahoe basin. Stream restoration and surveys are commonly conducted by the U.S. Forest Service as part of managing the national forest. Surveys have been conducted for most streams

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[12] Manley, P., and Lind, A., research wildlife biologists, USDA Forest Service, Pacific Southwest Research Station, Sierra Nevada Research Center, Davis, CA; Shaffer, H.B., professor, University of California-Davis, Davis, CA; Peacock, M., assistant professor, University of Nevada-Reno, Reno, NV; and Vredenburg, V., research associate, University of California-Berkeley, Berkeley, CA.

in the basin over the past 10 years by the U.S. Forest Service; stream habitat types are mapped as are occurrences of fish and amphibian species. Stream restoration has been actively pursued by the U.S. Forest Service and the California Tahoe Conservancy for the past 5 years; in many cases, that work includes before and after measurements of responses of plant and animal species, including aquatic, riparian, and upland associates.[13] The geomorphologic and water quality elements of these efforts are addressed in chapter 4, "Water Quality."

In addition to biological threats, lakes and streams face physical degradation as well. Firefighting often involves the collection of water from lakes to deposit on the fire; associated siphoning activities can potentially directly affect amphibian populations. An evaluation of the ecological value and sensitivity of various water bodies in the basin has not been conducted; thus activities such as siphoning may occur in areas where impacts could be high (e.g., Watson Lake).

Development has been responsible for the loss and fragmentation of marshes in the southern portion of the basin, specifically the Tahoe Keys development in the Upper Truckee Marsh. Surveys are being conducted to assess how development of this marsh has affected water birds and to evaluate the potential to restore affected species. Impacts to the physical condition of lakes, ponds, and marshes also are occurring in the basin, such as shoreline compaction and pollution from human uses. Anglers and hikers appear to have the greatest impact on the shoreline and nearby upland areas around existing lakes and ponds. The most common impacts include compaction of soil and removal of vegetation around the shoreline; however, some paved and dirt roads exist extremely close to shorelines creating the potential for erosion and conveyance of polluted runoff. Research has shown that degraded shoreline conditions can have a negative effect on the presence or abundance of aquatic species that occupy a site (Manley and Lind 2006).

Knowledge Gaps

In the last decade a watershed management approach to restoration activities in the Lake Tahoe basin has dominated. Although nutrient limitations and their shifts have been studied in Lake Tahoe (Jassby et al. 1994), it is unknown how atmospheric nitrogen loading has shifted nutrient limitation in the other lakes in the basin watershed (see chapter 3, "Air Quality"). Understanding the nutrient limitation is critical if we are going to promote the persistence of native fish or amphibian species in these ecosystems. It also is important for us to understand the degree to which nonnative fish are limiting amphibian populations in small lakes, and what

[13] Romos, S. 2008. Personal communication. Science and evaluation program manager, Tahoe Regional Planning Agency, 128 Market Street, Stateline, NV 89449.

options exist for effective reductions in these negative interactions. Understanding the movement patterns of nonnative trout, including barriers and distribution mechanisms, would greatly inform effective options for conservation and restoration of native species. We still lack information on the habitat associations and population dynamics of Pacific treefrog and the two aquatic-system-associated garter snakes. Population models and spatially explicit landscape evaluations of habitat conditions and values have not been developed for any amphibian or aquatic snake species. Management agencies are considering attempting to reintroduce the mountain yellow-legged frog into multiple locations in the basin; additional assessment and evaluation are recommended to establish an information-rich foundation for a reintroduction plan.

Uncertainties and concerns exist for native fish populations, as well. Restoration of native trout has been initiated at Fallen Leaf Lake. It is important to follow the effect of this restoration effort on all aspects of the lake's ecology and limnology. In particular, measurements are recommended to determine the lake's responses—nutrient, primary and secondary production—to the reintroduction. Overstocking of native trout in the lake, for example, could lead to trophic cascades and either increase or decrease the lake's clarity. Most appropriately, this study effort would occur throughout the life cycle of the trout or until they are extirpated from the lake. Beyond the Lahonton cutthroat trout, little information exists about the status of native fishes (e.g., sculpin or redside-shiner).

These issues and uncertainties suggest the following key management questions:

- Which lakes and other aquatic systems should receive priority management attention, and what actions should be undertaken to restore desired ecosystem values to each?
- What spatial and temporal strategy of restoration and management actions can be employed to maximize learning to inform future management decisions in aquatic systems with like conservation needs?
- What monitoring targets and sample techniques will best support adaptive management of Lake Tahoe's aquatics systems and their biota?

Research Needs

Following are other aquatic ecosystem research questions:

(**OE1**) What are the limiting factors of production for other lakes in the Tahoe basin? Do variations in limitation affect secondary production and the ability to support fish and amphibians?

(OE2) What are the ecological and limnological impacts of native fish reintroduction into Fallen Leaf Lake? What are the long-term changes to the lake owing to introductions and alterations to the lake's biota? What impediments (e.g., stream habitat, or secondary production) need to be overcome to produce a self-sustaining population of native trout in the lake?

(OE3) What was the historical progression of occupancy of lakes and streams by nonnative fishes, and how does it correspond to changes in the distribution and abundance of native aquatic fauna?

(**OE4**) What is the status of populations of amphibians and aquatic snakes in the basin, including habitat needs, population dynamics (e.g., metapopulation structure), prevalence of disease (particularly chytrid fungus) and distributions that are important to maintaining or restoring populations?

(OE5) What is the distribution and abundance of native fishes in lakes and streams, and what factors regulate their populations?

(OE6) What is the chemical and physical status of lentic ecosystems in the Tahoe basin (other than Lake Tahoe), including measures of nutrients and pH?

(**OE7**) What performance measures—including macroinvertebrates, presence and abundance of plants and animals, and other ecological metrics—can be used to assess the condition and restoration effectiveness in maintaining, restoring, and rehabilitating the biological diversity and ecological function, and in monitoring conditions of lake and stream ecosystems?

(OE8) What is the limnological and ecological status of Star Lake and how has it changed in response to human stressors?

Urbanization

The urbanization of natural landscapes is a substantial factor in the erosion of biological diversity in the United States (Hansen et al. 2005, Theobald 2005). Urbanization imposes a suite of stressors for ecological communities, including habitat loss, alteration and fragmentation, reduced soil quality, increased soil erosion, water and air pollution, introduction of nonnative species, and human disturbance, all of which have negative consequences for native species (Baxter et al. 1999, Donnelly and Marzluff 2006, Fernández-Juricic 2000, McDonnell and Pickett 1990, McKinney 2002, Miller et al. 2003, Miller and Hobbs 2000, Pouyat et al. 1994, Steinberg et al. 1997). Urbanization can lead to lower diversity (structure and composition) of native plants and animals, losses of vulnerable species, and increases in exotic and generalist species. After the resource extraction era in the Lake Tahoe basin ended in the early 1900s, many wildland areas in the lower elevation montane zone began undergoing conversion to urban uses, with subsequent changes in the amount and quality of habitat for wildlife. However, if well managed, it is thought the basin's urbanized areas could maintain much of their native plant and animal diversity.

Knowledge Gaps

Numerous impacts of urban development on plant and animal communities have been documented in the Tahoe basin (e.g., Heckmann et al. 2008, Manley et al. 2006, Schlesinger et al. 2008). Nonetheless, many important uncertainties remain regarding the relative role of various urban-related stressors, such as habitat loss, fragmentation, or alteration, in affecting negative changes in population viability of species of concern or community integrity. The dynamic nature of native forest communities makes balancing social, ecological, and economic objectives a challenge (Folke et al. 2005). Stressors associated with urbanization act at both local and landscape scales; understanding the individual and interacting effects at multiple scales is key to managing future urban and recreational growth in a manner that conserves and maintains biological diversity and ecological integrity of native ecosystems.

Wildlife—

Land development for housing, commercial enterprises, and infrastructure decreases the amount and changes the distribution and quality of habitat for wildlife. Habitat quality for wildlife species also may be affected by forest and fire management practices in and near urban areas, which can in turn lead to structural and compositional changes in those forests (see "Fire and Fuel Management" and "Old-Growth and Landscape Management" sections in this chapter). Wildlife species most likely to be negatively affected by these changes are those that are primarily associated with lower elevation montane forests, and those that have large area requirements and small populations in the Tahoe basin, such as northern goshawk, California spotted owl, spotted skunk (*Spilogale putorius*), and bobcat (*Lynx rufus*). Passerine bird species that are associated with old-growth forests or the understory habitats of older forests also may suffer population declines.

Recent research conducted by Manley et al. (2006) has identified a number of species, species groups, and community metrics that respond to various aspects of urbanization, including development and human activity. They studied birds, small mammals, large mammals, ants, and plants. In general, birds and large mammals were most negatively affected by development, followed by individual species of small mammals and ants. Understory bird species were most sensitive to surrounding development, as were mustelids and black bears. Coyotes showed no difference in frequency of occurrence with development, and domestic dogs were prevalent throughout all development areas. In contrast, few domestic cats were detected. Forest structure and composition did not change within undeveloped parcels in response to surrounding development, with the exception of lower snag and log densities and an increase in the richness of exotic plants with higher development. Not all relationships were linear; rather, in some cases sudden shifts in species abundance and composition were observed. But it is not known at what stage of development—earlier or later—that such responses may manifest. The study primarily identified patterns of richness and abundance, which suggest cause-effect relationships that can be confirmed and clarified through research focused on individual questions.

In general, concentration of humans in urban environments leads to increased disturbance of wildlife habitats and mortality (from traffic and recreation), increased densities of exotics and domestic species (especially pets), and, in certain circumstances, habitat enrichment (including increases in food, cover, or water resources that can confer an advantage for certain species such as black bears and coyotes). Determining the site-specific impacts from high-intensity recreation and increased numbers of exotic species in the Tahoe basin's urban forests is an outstanding information need. Pets and humans can contribute to the spread of exotic plants and diseases, with areas subjected to higher rates of human visitation at greater risk. Exotic plants pose a problem for wildlife species if they outcompete native plants that provide food or other essential resources, or if they lead to changes in habitat structure. Currently, the basin has few invasive exotic plants, so they do not pose a particularly high ecological risk to wildlife; however, effective measures to reduce the potential for future establishment of exotic plants are needed.

Habitat enrichment in the form of supplemental food and cover is varied but common in developed areas of the Lake Tahoe basin. It is likely that habitat enrichment has increased the prevalence of some bird species, coyotes, and black bears, and increased conflicts with humans (Manley et al. 2006). The effects of habitat enrichment on distributions and population sizes of these and other species are not clear. Habitat enrichment may lead to population growth in select species only in developed areas, or in the whole basin more widely, or it may simply cause shifts in animal species distributions, especially if animals abandon formerly suitable sites and move to urban areas. For example, Beckmann and Berger (2003a, 2003b) found in a study of black bears in Lake Tahoe that urban bears had smaller home ranges and spent significantly less time foraging compared to wildland bears. Urban environments offer enriched and novel sources of food (e.g., garbage bins and coolers) and cover (e.g., cabins and decks), making urban areas desirable for foraging and denning. Enriched environments typically have a greater carrying capacity than native ecosystems, with unknown long-term consequences.

Plants—

Forest structure and composition is affected by urbanization in the Lake Tahoe basin. Manley et al. (2006) found that on undeveloped forest fragments (most of which were >1 ha), snag and downed wood densities declined and exotic plant species increased with increases in the amount of surrounding development. McBride and Jacobs (1986) found even greater changes in the urban matrix, characterized by decreased tree density and cover and increased tree species richness and age-class diversity.

Exotic plant species are an immediate problem locally in certain areas of the Lake Tahoe basin. Elsewhere most exotic plants originally were introduced for horticultural uses by nurseries, botanical gardens, and individuals (Reichard and White 2001), but it is unclear whether plants used in horticulture are an important source of invasive species in the Lake Tahoe basin. Many of the established invasive plants in the basin (Donaldson 2004) appear to be plants that have spread into disturbed areas, particularly along roadsides, and that have no obvious horticultural application.

The nutrient applications and water uses on residential and commercial landscapes can have adverse effects on local nutrient cycles, allowing nutrients in runoff and drainage to reach local water bodies (e.g., Bormann et al. 2001). Surprisingly, conventional turfgrass landscapes may retain applied nutrients better than multispecies landscapes that may have been designed for low nutrient and water inputs (Ericksen et al. 2001, 2005). Regardless of landscape type, having more knowledge about the nutrient status of landscape plants allows more efficient application of fertilizer (e.g., Scharenbroch and Lloyd 2004).

Revegetation efforts on roadside edges are common projects within the Lake Tahoe basin, particularly because they are believed to decrease runoff and soil leaching. Not all revegetation projects have been successful; however, the use of locally adapted plant ecotypes may best support the steep elevation and dramatic precipitation gradients in the basin. In cases where native plant revegetation projects have been successful, there can be concerns about alteration of genetic structure of native plant communities (e.g., Gehring and Linhart 1992).

Construction projects in the basin often occur close to large trees, and precautions are always taken to retain these trees as visual and ecological amenities. Regrettably, these trees often die prematurely, possibly from damage sustained by

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Urban forest lot, South Lake Tahoe, California.

roots during construction. Current practice is to protect the root zone that occurs inside the edge of the tree crown (the "critical root zone"), yet evidence from ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) excavations indicates that the maximum horizontal extent of conifer roots can be much greater than the crown edge (Berndt and Gibbons 1958, Curtis 1964, Greb and Black 1961, Hermann and Peterson 1969).

These issues and uncertainties suggest the following broad management questions:

- What aspects of urban development are most detrimental to conserving and restoring biological diversity and ecosystem integrity, and what facets of biodiversity are most vulnerable to urban stressors?
- What locations in the basin are most valuable for maintaining biological diversity, and what management approaches are most effective in minimizing the impact of urbanization?
- What risks do traditional landscaping and revegetation approaches pose to the introduction of nonnative native species to the basin, and what effective alternatives exist?

Research Needs

Following are urbanization research questions:

(**UR1**) What mechanisms determine observed declines in biotic diversity in the urban environments of the basin (e.g., habitat loss, habitat fragmentation, habitat alteration, disturbance, mortality from vehicles and pets)?

(**UR2**) Are there threshold levels of development at which sweeping changes in wildlife species abundances and ecological community composition occur?

(**UR3**) How does the current spatial pattern and extent of development affect connectivity of animal populations? Are there important areas (corridors, connectors) determined by the combination of fixed environmental characteristics (e.g., slope, elevation, or rock outcrops) and human development?

(**UR4**) Which urban forest types and sites are most impacted by recreation and exotic species (including pets)? Impacts include creating functional barriers, ecological constraints, and limitations to habitat availability. Studies are needed to determine how these impacts can be mitigated.

(**UR5**) Does habitat enrichment cause basinwide or local increases in geese (*Branta* spp.), coyote, and bear populations, or shifts in their distributions? Is enrichment leading to changes in the survival, reproductive success or behavior (e.g., habitat use or response to humans) in these species? Are those changes likely to put those species or humans at demonstrably greater risk or otherwise affect area- and disturbance-sensitive species?

(UR6) Are roads serving as conduits for invasive species into the Lake Tahoe basin? Are plants used in residential and commercial landscaping contributing to invasive species problems in Lake Tahoe basin wildlands?

(**UR7**) Which plant species, plant ecotypes, and planting techniques are best for enabling successful establishment of native species in disturbed roadside areas? What plants and planting techniques should be employed at the greater basin scale (e.g., by elevation and longitude), and at local scales (e.g., road shoulder versus exposed steep slope)?

(UR8) Would increased use of water-efficient plants for residential and commercial landscaping result in lower demands on water supplies within the basin, and less runoff? Would use of nutrient-efficient plant genotypes for home and commercial landscaping result in lower fertilizer application rates?

(UR9) What is the effectiveness of various conservation measures to maintain large trees in developed areas? What is the relationship between stem DBH and maximum horizontal extent of rooting for large trees (e.g., Jeffrey pine, sugar pine [*Pinus lambertiana* Douglas], incense cedar [*Calocedrus decurrens* Torr. Florin], red fir, and white fir) retained in developed areas of the Lake Tahoe basin? How should the critical root zone be designated for each species to preserve most surface roots, while acknowledging the realities of construction operations?

(**UR10**) What is an effective set of indicators—including plant, animal, and other ecological community metrics—that can be used to assess the effects and effectiveness of forest management efforts, and to monitor biological diversity in and adjacent to urbanized areas? How should urban parcels be prioritized for interventions to improve ecological function?

(UR11) What is the relative importance of potentially competing uses (e.g., reducing fire risks, or maintaining biological diversity) of urban lots in the urban-wildland interface? What are the tradeoffs among competing uses, both short and long term, including maintaining and restoring biological diversity?

Recreation

Outdoor recreation is a primary activity for residents and visitors of the Lake Tahoe basin. Many forms of recreation are available in the basin. In the summer, backcountry hiking, biking, mountain climbing, horseback riding, and fishing are popular. Activities on Lake Tahoe are numerous, including swimming, kayaking, sailing, speed boating, fishing, and jet skiing. Outdoor recreation is just as popular during the winter, including downhill and backcountry skiing, snowshoeing, and snowmobiling.

Knowledge Gaps

Residents and visitors who hike or bike can disturb the activities of many vertebrate species, particularly species at higher trophic levels, such as northern goshawk, California spotted owl, American marten, and bobcat. Hiking and biking pose slightly different challenges and stresses to wildlife species—hikers have a longer residence time, thus having a greater impact on species sensitive to human presence, whereas bikes move quickly, posing a risk of physical impact, and some trails have a steady stream of users potentially posing barriers to wildlife movement. Dogs are common hiking companions in the Tahoe basin; they chase and sometimes kill wildlife species, particularly lower trophic-level species, such as mice, chipmunks, squirrels, and ground-dwelling birds.

Peter Goin

Ski slope in autumn, Mount Rose ski resort, Nevada.

Off-highway vehicle use in the Lake Tahoe basin during the summer and winter is restricted to relatively circumscribed areas; however, in the winter, snowmobile use can be widely dispersed in undesignated areas (e.g., the McKinney-Rubicon trail). Snowmobile use can affect resident wildlife species at times of their highest physical stress. The U.S. Forest Service recently completed route mapping for OHVs, and it is still evaluating designations. A study of the effects of summer and winter OHV use on American marten was conducted in the McKinney-Rubicon area, as well as at a southern study area on the Sequoia National Forest (Zielinski and Slauson 2008). Another study still underway is looking at community-wide responses of wildlife to summer OHV use, including study sites throughout the basin.[14]

Downhill ski areas have several potential adverse effects on wildlife: (1) forest losses and fragmentation (only shrub and grass layers remain on ski slopes), which affect late-seral associated species, such as American marten, northern goshawk, California spotted owl, and spotted skunk; (2) high human disturbance during daytime on ski slopes may create barriers to habitat use and between-habitat patch movement for diurnal species; (3) changes in forest cover and human disturbance may create "sink" habitat for American marten; (4) night lighting and grooming on

[14] Manley, P.; Campbell, L. 2008. Personal communication. Research wildlife biologists. USDA Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

ski slopes may interfere with the behavior of nocturnal species; and (5) losses of snags in forested areas between ski runs owing to hazard tree removal can locally reduce wildlife habitat quality. In the Lake Tahoe basin, it is important to know the extent to which existing or potential ski resort expansions may affect the persistence of basin wildlife populations.

The spatial extent of intensive cross-country skiing is limited, thus it does not appear to pose a major risk to wildlife. It is likely that although usage can be substantial locally, sufficient management structures are in place (including snow grooming, and bridges across streams), and monitoring to determine wildlife use in cross-country ski areas is probably the appropriate data-gathering investment at this time.

These issues and uncertainties suggest the following management questions:

- What recreational activities are the most detrimental to wildlife resources, and are there land management actions that can reduce impacts while accommodating those activities?
- What are appropriate measures of recreational impacts on wildlife, and how might those measures be integrated into monitoring programs?

Research Needs

Following are recreation research questions:

(RE1) What are the characteristics of key locations inhabited by animal species of concern that are sensitive to summer or winter recreation activities? Where do these key locations occur, for purposes of recreation planning and study design?

(**RE2**) What combination of summer recreation activities (motorized and nonmotorized; amount, timing, and location) and environmental factors present a risk of site abandonment by sensitive wildlife species?

(RE3) What are the combined effects of snowmobile use (amount, timing, and location) in association with particular environmental factors that present a risk of site abandonment by resident wildlife species?

(**RE4**) To what degree are dogs impacting wildlife populations and communities?

(RE5) Are the locations of OHV routes (summer and winter) likely to pose biologically significant barriers to one or more species with large area requirements?

(**RE6**) Are existing ski areas predominantly occupied by male martens, and if so, does the extent of this population response pose a threat to the persistence of this species in the Tahoe basin?

(RE7) To what degree may existing and potential expansions of ski areas fragment the landscape mosaic for species that have large home ranges and are dependent on closed-canopy forest conditions for nesting, foraging, and movement?

(RE8) What tools can be developed to assess how best to manage recreation and habitats to reduce people-wildlife conflicts?

(**RE9**) What tools are most effective and efficient in measuring recreation use of various types in a manner that informs interpretations of effects on biological diversity and ecosystem function?

Climate Change

Conservation planners and managers have acknowledged the reality of climate change and incorporate expected changes into their land and resource planning efforts (McCarty 2001). Despite uncertainty in many aspects of climate predictions, there is widespread agreement that in California and Nevada, mean summer temperatures will increase, there will be more extreme heat events, residual summer snowpacks will decrease, and consequently the ranges of organisms that are restricted to higher elevations will shrink (Hayhoe et al. 2004, Kim et al. 2002). Disturbance regimes that are climate dependent also will be subject to changes. Fires in the Lake Tahoe basin are expected to be more frequent and intense under higher average temperature regimes (Taylor and Beaty 2005, Westerling et al. 2006). Organisms will respond to these changes in species-specific ways, creating communities that may have no modern analogue (Ibáñez et al. 2006, Millar et al. 2006).

Knowledge Gaps

The span of elevations in a relatively small geographic area makes the Lake Tahoe basin particularly vulnerable to change in species distribution and abundance because of the limited amount of suitable habitat for many species. It also makes the basin a valuable test case for how plants and animals may respond to climate change. The first challenge is to obtain precise and accurate measurements of climatic conditions through meteorological monitoring stations. Currently, three weather-monitoring stations are located in the basin, and a Global Observation Research Initiatives in Alpine Environments (GLORIA) monitoring site was established on Freel Peak in 2006 (see http://www.gloria.ac.at/ for more information).

The proper targets or desired conditions for ecosystem management are not obvious given the complex realities of organism responses to climate change (Harris et al. 2006). Research for such a contextual stressor as climate change can be approached in multiple ways. One approach to answering questions regarding species responses to climate change is to build statistical models of species occurrences (as climate and soil envelopes) by relating present-day distributional ranges to climate and soil variables. The models are then applied to climate scenarios that have been generated by global circulation models or regional climate models (e.g., Ibáñez et al. 2006, Kueppers et al. 2005, Sala et al. 2001). An alternative approach, most suitable for intensive work on individual species, is to build process-based, mechanistic models of species responses to the environment, and to apply these models to climate scenarios. That approach may be particularly advantageous when multiple environmental values are being considered (e.g., carbon sequestration by trees) or there are strong feedback effects.

These issues and uncertainties suggest the following broad management questions:

1. What are the anticipated responses of wildlife, fish, and vegetation communities in the Lake Tahoe basin owing to climate change? What are the appropriate responses of land and resource managers to changes in these natural communities?
2. How can ongoing monitoring programs and research efforts be adjusted to provide the information necessary to allow managers and decisionmakers to integrate climate change into management planning and implementation?

Research Needs

Following are other climate change research questions:

(CL1) How is climate changing in and around the Lake Tahoe basin? (Note: this basic information, coupled with question 2 above, can also be used to support research projects proposed in the "Water Quality" and "Soil Conservation" chapters)

(CL2) How is climate change predicted to change the elevational boundaries between ecosystem types (e.g., montane and subalpine forest, and subalpine and alpine zones) in the Lake Tahoe basin over the next 10 to 100 years?

(**CL3**) How is climate change predicted to change the ranges and populations of plant and animal species of concern over the next 10 to 100 years?

(**CL4**) What are an effective set of indicators of the physical and biological changes that may occur as a result of climate change?

(CL5) How might management practices be altered in response to the projected environmental effects of climate change?

Summary of Near-Term Research Priorities

The research needs identified under the ecology and biodiversity theme represent a coherent set of information that is needed to reduce uncertainties and improve the probability of achieving desired conditions for living resources and their habitats in the next 5 to 10 years. The near-term value of some information is greater in some cases than in others. In many cases, steps toward building a knowledge base are most efficient when pursued in a particular sequence. In other cases, individual pieces of information are highly valuable in their own standing in that they can positively contribute to meeting management objectives as soon as they become available. Research needs that match one or both of these situations are considered near-term research priorities, and given equivalent opportunities for funding, they are recommended for funding and implementation first. Near-term research needs and priorities are synthesized below.

Subtheme 1: Old-growth and landscape management—
The ultimate objective of forest management is to restore and maintain forest health and resilience such that forests maintain and restore their full range of functions and native biological diversity, and thereby retain their resilience and assocated ecosystem services upon which human communities in the basin depend. The primary uncertainty limiting management's ability to meet this objective is a clear understanding of desired environmental conditions, and when and where to create them. Specific questions pertain to the historical amount and distribution of forest structural conditions, associated plant and animal species composition, and how to translate historical conditions into target conditions for the future that will enable forested ecosystems to adapt to future environmental stressors without the loss of function or biological diversity. Old forests are of particular concern and interest, because, despite the maturity of existing forests, it is apparent that extant forests have lost some ecological complexity associated with old forests, and therefore species and functions restricted to old forests are rare and most at risk from uninformed management. Finally, development of robust measures of forest biological diversity and resilience are recommended to enable simple and effective tracking of management progress and success.

Subtheme 2: Fire and fuels management—
One of the greatest ecological risks associated with fire is the uncertainty associated with the effects of fuel reduction treatments—both their effectiveness in changing fire behavior, and the unintended consequences of treatment effects on other ecological conditions, such as biological diversity and forest ecosystem resilience. The near-term research needs pertain to addressing risks and uncertainties

posed by current management activities, which target fuel reduction treatments on tens of thousands of acres without a specific understanding of the ecological consequences. Therefore, near-term research needs include improving the understanding of the effects of various types and intensities of treatments on the spectrum of ecosystem management objectives, including but not restricted to fire behavior. Of primary concern is the fate of terrestrial species and processes, because they are directly affected by forest conditions. It would be most efficient to develop and test silvicultural prescriptions in the course of addressing near-term research priorities, as opposed to after ecological risks are more clearly understood. Once the primary ecological objectives at risk related to actions of reducing the threat of catastrophic wildfire are understood, it is important to develop simple and informative measures of their status for long-term monitoring.

Subtheme 3: Special communities management—

The conservation and restoration of special communities in the basin are best served by similar sets of information: (1) maps of current location and condition throughout the basin, (2) reference conditions based on historical data and other relevant data sources, (3) evaluation of the effectiveness of restoration approaches, and (4) the development of performance measures to assess status and restoration effects. A few unique information needs are associated with individual special communities. In aspen communities, techniques for converting conifer-encroached stands back to aspen-dominated habitats is a primary information need. Fens and meadows are under an unknown level of threat from various human activities. Information on the current status of marshes is lacking. Finally, detailed information on genetic and environmental sensitivities of Tahoe yellow cress are needed to aid population restoration efforts of this endemic species.

Subtheme 4: Aquatic ecosystem restoration—

The emphasis of aquatic ecosystem research is on conservation and restoration of vertebrate biota in Lake Tahoe and the conservation of species in the rich array of other aquatic ecosystems around the basin. In Lake Tahoe, the uncertainties with the greatest potential impact on management are those associated with the interactions between nonnative and native plant and animal species. These interactions have potential consequences for biodiversity, lake clarity, and near-shore aesthetics. Research on measures to control established nonnative species is urgently needed, and is best pursued through an adaptive management approach using information from careful assessment of pilot projects to guide longer term management strategies. Restoration of native fishes in Lake Tahoe presents a steep challenge, and information on the ecological interactions is key to making progress. The other aquatic ecosystems are in need of more basic information: (1) the status of vertebrate populations and communities, and (2) factors limiting the ability of sites to support native species. Once these kinds of information are developed and better understood, it would then be appropriate to develop efficient measures that can be used to track conditions over time.

Subtheme 5: Urbanization—

Research recently conducted in the Lake Tahoe basin identified substantial and unexpected effects of urban development and human activities on various elements of biological diversity (Manley et al. 2006). The patterns observed differed by taxonomic group (i.e., birds, small mammals, mammalian carnivores, ants, and plants), among species (some were sensitive, whereas others were not), and by type of human disturbance (e.g., habitat loss, habitat alteration, habitat enrichment, or different types of human activities). The results of that work suggest the need to understand mechanisms of key responses such that development and management can be conducted in a manner that minimizes and mitigates negative effects on biological diversity. Questions of particular priority pertain to better understanding thresholds of change in habitat loss, habitat alteration, or habitat use indicated by past research, specifically changes observed at 30 to 40 percent development. Above this threshold, it is unclear what happens, but sites likely become sinks, traps, or abandoned by a wide array of species. In addition to site-scale mechanisms, landscape-wide modeling is needed to understand the implications of existing results and facilitate the rapid evaluation of the implications of new information on landscape design and management priorities. Finally, as in other subthemes, the development and testing of effective measures for use in monitoring and assessment are recommended, as vulnerable species and target ecological objectives in more urban areas are clarified.

Subtheme 6: Recreation—

Recreational uses have been identified to have substantial effects on the occupancy and abundance of many and diverse species, based on multiple research projects. Alternatively, species thought to be impacted by certain recreational activities (e.g., effects of OHV use on occurrence of American marten) did not exhibit negative responses. Specific uncertainties in the Tahoe basin pertain to the effects of dogs on retaining biological diversity in more urban environments, and the effects of ski areas on montane obligates, namely American marten. Although population sizes of northern goshawk and bald eagle are limited, their sensitivity to the presence of people has important implications for the management of events and ongoing recreational uses in the vicinity of known use sites. Effective measures of use and effects are lacking and their development will be important for monitoring.

Subtheme 7: Climate change—

Climate change is perhaps the ultimate source of uncertainty, and arguably poses a high environmental and economic risk. Under such circumstances, information needs start at the basics. In the case of ecological elements and processes, this translates to applying existing and new information to modeling potential responses—plant and animal ranges and associated effects on population sizes, species interactions, and ecological services—to predicted or potential climate change and associated broad-scale environmental responses. It is important for modeling to be conducted in the basin, as opposed to relying on modeling outside the basin or at larger scales because detailed information will be needed to inform management agencies about how they can respond to potential threats. As with all other subtheme areas, as information is accrued, the development of effective and reliable measures of key population and community metrics for monitoring is recommended.

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Chapter 7: Integrating the Social Sciences in Research Planning[1]

Derek Kauneckis[2] and David Halsing[3]

Introduction

The social sciences were included in the science plan to explicitly recognize that the processes underlying environmental degradation, as well as environmental conservation and restoration, are fundamentally based on human decisionmaking. Effective management of the natural environment relies on a well-grounded understanding of human behavior, the interaction of social and natural processes, and linking information from the social sciences to policymaking. This has become an explicit component of environmental management in the Lake Tahoe basin with the inclusion of the concept of the "Triple Bottom Line" in the Pathway planning process. This stresses that management should consider the well-being of the environment, the economy, and the community in the development of new regional plans (Pathway 2007). The term social science is used here to refer to the study of human behavior, typically through the use of the scientific method. The definition has been kept as broad as possible and includes different disciplinary approaches such as economics, sociology, and political science, as well as interdisciplinary fields of study such as community planning, decision sciences, policy evaluation, and socioeconomic development. It also includes applications of social science methods and knowledge in management decisions such as data collection methods, monitoring, evaluation, modeling, organizational behavior, and policy process evaluation.

Although there have been numerous academic studies calling for integrated environmental assessment that explicitly include the social sciences (see Cortner 2000, Endter-Wada et al.1998, Mascia et al. 2003, Meyer 1997, Redman et al. 2004), to our knowledge, this is the first attempt to include a social science chapter in a science plan. We have attempted to develop both a broad framework for understanding the collection and use of the social sciences as well as specific types of information requested by stakeholders in the Lake Tahoe basin. There are a wide variety of methods in the social sciences that can be brought to bear on the types of research identified in this chapter. These range from qualitative interviews to quantitative surveys, cost/benefit and cost-effectiveness analyses, program evaluation, public

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management, and policy analysis. All methods involve tradeoffs in terms of the reliability, validity, replicability, and overall utility for answering specific management needs. For some questions, such as conflict resolution and community vision development, qualitative interviews and consensus-building workshops are likely most appropriate. In others, such as ranking cost-effectiveness of various projects or models of projected fiscal revenues, more quantitative methods are preferred. The method to be used depends on the specific research questions and the methods ability to provide useful information for management decisions.

The goals of this chapter are to (1) identify social science data and research needs for management objectives that are not directly environmental, (2) describe the research needs necessary to improve policy design and implementation for managing environmental conditions, and (3) develop a framework for prioritizing social science research needs in areas that focus on the interaction between the human and natural environments. In many ways, the social sciences could be considered an overarching theme that encompasses all human-caused drivers of environmental change. However, in following the organization of issues set out in various management plans and process documents (see table 1.1, chapter 1), this chapter focuses on five subthemes determined as unique to Lake Tahoe basin social sciences: recreation, transportation, economics, noise, and scenic resources. Additional areas of research interests and cross-cutting issues identified by the various stakeholders are discussed throughout the chapter. Issues that were common across the subthemes have been organized into a section of "meta-themes" and include the following topics: collaborative information management; community management, program evaluation, policy design and policy process evaluation, management of fire and natural hazards, and climate change impacts.

Methodology

Social science research on the Lake Tahoe basin is limited in comparison to the amount of natural science investigation and data collection. The 2000 Lake Tahoe Watershed Assessment states that "relatively little comprehensive or integrated social and economic analysis has been done in the basin to date. Nearly all the recent economic studies conducted in the basin have been focused either on a specific sector or geographic region" (Murphy and Knopp 2000). There are challenges to even simple data collection and analysis in a watershed that spans two states, five counties, and one incorporated municipal area, and includes federal, state, and utility district lands as well as several special government units and private landholdings.

Information on the social science research needs for the Tahoe basin was gathered using a number of different methods. First, relevant literature on the various subthemes was reviewed. Documents included general background work on the role of social science in environmental management (Cortner 2000, Imperial and Kauneckis 2003, Mascia et al. 2003, Redman et al. 2004, Sturtevant et al. 2005). Reports specific to the Tahoe basin included the Lake Tahoe Watershed Assessment (Murphy and Knopp 2000), the Pathway Process documents (TRPA 2006c, 2006d), the Tahoe Regional Planning Agency (TRPA) Threshold Evaluations (TRPA 2006a), the Environmental Improvement Program (EIP) (TRPA 2001b, Tahoe Federal Interagency Partnership 1997), and regional work such as the Sierra Nevada Ecosystem Project (Centers for Water and Wildland Resources 1996, 1997; Elliott-Fisk et al. 1996; Nechodom et al. 2000a, 2000b) and other basinwide assessments of management and data needs (Halsing et al. 2005, Nechodom et al. 2004, Tracy 2004). Private sector activities and concerns related to economic health and community well-being were examined in various economic assessments, regional strategic plans and community development forums (Jones and Stokes 2000; North Lake Tahoe Resort Association 2004, 2007; TRPA 2006b). Particular attention was paid to studies that inform the subthemes considered in this chapter.

From the literature review, a list of topics for discussion was sent to a wide range of Tahoe stakeholders including federal, state, and regional resource management agencies; local governments and utility districts; representatives from chambers of commerce and other business associations; and environmental organizations. A letter was sent explaining the Tahoe Science Consortium's (TSC) purpose in developing a Tahoe basin science plan, asked the recipient to comment on the relative importance of the items on the list, solicited additions or modifications, and requested followup meetings and conversations. Written and verbal responses to the letter were compiled and are discussed in the relevant sections below.

The third step involved a series of focused meetings and workshops held with two important stakeholder groups: natural resource management agencies and chambers of commerce.[4] Each of the five subthemes was discussed with the resource management agencies to determine the science needs of the participants. Workshops held with both the north and south shore chambers of commerce were less explicitly oriented on the goals of this chapter, but rather sought input on developing measures and indicators of the more broadly defined concept of sustainable communities. The input of all stakeholders was reviewed to discern common areas

[4] The full array of participating organizations is too numerous to report here; however, the "Acknowledgments" section of this chapter lists the most substantive contributions and key participating organizations.

of interest for social science research and those that might best serve the widest audience. Emphasis was placed on those topics that were within the regulatory mandate of one or more Tahoe basin agencies, or that could best serve the needs of environmental management and offered opportunities for collaboration in funding, data collection, and distribution of information.

The first draft of this chapter was sent to registered attendees of the TSC's Tahoe Science Symposium, which took place in October 2006. Major themes and findings were presented to attendees and discussed in a 3-hour breakout session. Input was included in a second draft of the chapter, that was then sent to social scientists and other stakeholders who work in the Tahoe basin. Thus, key local participants have had a number of opportunities to correct, modify, and add contributions. A draft of the science plan was sent for external review by the U.S. Environmental Protection Agency, with comments received in July 2007. Reviewer comments and suggestions have been fully addressed through chapter revisions, in the response to reviewer's comments, or with additional analysis. Based on the information collected at this stage, a list of research needs was identified and is presented in the following tabulation. These included a broad array of issues related to monitoring, research, and application of social science data and methods. Individual items are listed within subthemes and organized according to whether the issue represented data collection and consolidation, monitoring for a specific management need, public agency management and collaboration, or program evaluation and policy design.

Summary of social science research needs identified

Recreation subtheme

Data collection and consolidation:
- Development of a set of core questions to be used in all recreational surveys within the Tahoe basin (R1)[a]
- Development of a 3-year recreational survey cycle as suggested by the Tahoe Regional Planning Agency (TRPA) (R2)
- Track recreation accomplishments and needs over time at the basin level (R3)
- Collection and consolidation of recreation data at larger spatial scales (e.g., regional and basinwide) (R4)

Monitoring for management needs:
- Research recreational capacity at the site and regional level (e.g., South Shore/basin) (R5)
- Quantitative evaluation of adequacy of current measures (e.g., TRPAs PAOT system and indicator) (R6)
- Statistical analysis of the factors associated with current measures of recreational quality (R7)
- Investigations of the spatial and temporal variation of the environmental impacts of recreational activities (R8)

Recreation subtheme (continued)

- Investigations of the link between recreational activities and associated infrastructure (R9)
- Research on crowding-out owing to price, incompatible activities, and infrastructure (R10)
- How vulnerable are recreational facilities to natural hazards? Can resiliency to such hazards be improved? (R11)
- How vulnerable are recreational facilities to climate change? Can resiliency to such hazards be improved? (R12)

Public agency management and collaboration:

- Develop common data-sharing infrastructure and coordination of data collection efforts (R13)
- Knowledge-sharing about effective approaches used in other alpine resort communities (R14)

Transportation subtheme

Data collection and consolidation:

- Increase the consistency, spatial and temporal coverage of current data collection efforts (T1)
- Increase collection frequency of congestion and vehicle-hours of delay (VHD) data (T2)
- Collection of bicycle use data at the basin level (for paved and unpaved trails) (T3)
- Collection of public transit ridership data to and within basin (T4)
- Study public perception of congestion, traffic levels, and transportation issues (T5)

Public agency management and collaboration:

- Increased collaboration in data collection to serve needs beyond transportation planning, such as associated infrastructure and community development (T6)
- Centralize the collection, inventory, and distribution of transportation data at the basin level (T7)
- Develop a Web-based information source about all basin-level public transportation systems (e.g., route, fares, ridership, etc.) (T8)

Program evaluation and policy design:

- Development of a transportation indicators for environmental impact, person-hours of delay and other measure of basinwide transport (T9)
- Statistical study of the link between changing demographic characteristics and travel patterns (T10)
- Feasibility study of a commuter bus from South Shore to Minden and Gardnerville areas and increased ferry service (T11)
- Research on travel behavior and consumer choice within the Tahoe basin (T12)
- Research on the impact of increased second-home ownership on transportation planning (T13)
- Research on transportation options for lower-income workers and the link to affordable housing (T14)
- Evaluation of effective policy options for increasing public transit ridership (T15)
- Evaluation of effective policy options for managing illegal parking at recreational facilities (T16)
- Evaluation of transportation research and use of alternative transportation in other alpine resort communities (T17)

Transportation subtheme (continued)

- Examination of the linkages between transportation and recreation, land use, economics, and other management issues (T18)
- How vulnerable is the transportation infrastructure to natural hazards? Can resiliency to such hazards be improved? (T19)
- Develop long-term predictive models of vehicle use, transit ridership, and demographics (T20)

Economics subtheme

Data collection and consolidation:

- Develop a reporting system of business/construction permits and permitting costs (E1)
- Increase data collection and analysis of housing trends at the community and basin level (E2)
- Increase data collection and analysis of employment trends at the community and basin level (E3)
- Increase data collection and analysis of tourism trends at the community and basin level (E4)
- Increase data collection of community quality of life variables (e.g., school enrollment, arts funding, etc.) (E5)
- Collect and consolidate basin-level demographic data (e.g., part-time residents, homeownership, commuters, etc.) (E6)
- Increase data collection on socioeconomics of populations such as low-income workers, Latinos, and Washoe Tribe members (E7)
- Increase data collection on affordable housing for year-round residents, public sector employees, and service workers (E8)
- Research on the development and use of community sustainability and well-being indicators for directing long-term planning (E9)

Monitoring for management need:

- Research the impact of redevelopment projects on housing, employment, and tourism (E10)
- Investigate the linkages between housing and land values, environmental quality, environmental regulations, tourism, economic health, and community well-being (E11)
- Research on the competitiveness of Tahoe-based businesses and leveraging the local Tahoe businesses (E12)
- Predictive, simulation modeling and forecasting of interaction of housing prices to job, wages, tourism, regional economy, and environmental regulations (E13)
- How vulnerable is economic and community well-being to natural hazards? Can resiliency to such hazards be improved? (E14)
- How vulnerable is economic and community well-being to climate change? Can resiliency to climate change be improved? (E15)

Public agency management and collaboration:

- Develop a community and basinwide information sharing infrastructure on economic and community well-being data (E16)
- Research into the system of collaborative funding involving both public and private sector for economic research (E17)
- Develop knowledge-sharing system on property valuation and housing dynamics in similar alpine tourism communities (E18)

Economics subtheme (continued)

Program evaluation and policy design:
- Evaluation, prioritization, and coordination of EIPs projects (E19)
- Feasibility studies of new environmental policy approaches (e.g., emissions trading, carbon markets, land coverage banking) (E20)
- Program evaluation of the effectiveness and cost-efficiency of existing environmental programs and regulations (E21)
- Research into effective policy options for increased affordable housing (E22)

Scenic resources subtheme

Data collection and consolidation:
- Data collection on public perceptions of the degree of light pollution and potential policy options (S1)
- Data collection on public perceptions of the scenic quality of the natural environment (e.g., forest, lake, ecosystems, etc.) (S2)
- Data collection on public perceptions of the scenic quality of the built environment (e.g., viewsheds, architecture, public space) (S3)
- Develop a meaningful TRPA Scenic Quality Indicator (S4)
- Develop community character indicators of the built environment (S5)
- Develop a scenic carrying capacity rating system (S6)

Monitoring for management need:
- Research into the links between redevelopment investment and the associated built environment (S7)
- Research on public valuation of scenic resources and link to associated management goals (S8)

Public agency management and collaboration:
- Increase the integration of TRPA indicators with other land management agencies (e.g., U.S. Forest Service, state, local governments) (S9)

Program evaluation and policy design:
- Feasibility study of new electric utility infrastructure being placed underground (S10)
- Feasibility study of a scenic easement and scenic development rights trading system (S11)
- Evaluation of effective policy options for increasing building design diversity (S12)
- Evaluation of effective policy options for improving scenic quality overall (S13)
- Evaluation of effective policy options for increasing investment in commercial, rental, and public facilities (S14)
- Evaluation of effective policy options for mitigating visual impact of private home development (S15)

Noise subtheme

Data collection and consolidation:
- Increase spatial and temporal extent of monitoring to capture single-event noise levels (N1)
- Research into the public perception and acceptability of noise levels (N2)

Noise subtheme (continued)
Program evaluation and policy design: • Evaluation of effective policy options for use of noise reduction technologies in off-road vehicles (N3) • Evaluation of effective policy options for decreasing violations of current noise levels (N4) • Evaluation of effective policy options for decreasing conflict over incompatible-noise level activities (N5)

[a] Codes in parentheses correspond to text in this chapter.

External reviewers explicitly requested prioritization of social science research needs and the inclusion of a more quantitative analyses. To develop the subset of higher priority items from the list identified in the tabulation above, an additional source of information was obtained through a Web-based survey of stakeholders conducted as an ancillary project by the University of Nevada, Reno (UNR). Survey questions were based on all comments received, as well as specific issue areas identified through conversations with data managers within each of the major resource management agencies, chambers of commerce, local governments, and environmental organizations. Invitations to participate in the survey were sent to approximately 350 natural scientists, resource managers, private and public interests, and other stakeholders identified as those who either attended the Tahoe Science Symposium or actively participate in public meetings with resource management agencies. Sixty-two responses were received from a wide variety of stakeholders (fig. 7.1). Details of the methods used and questionnaire format are available in Kauneckis and Copeland (2008).

Results from the survey are presented throughout this chapter and confirm earlier stakeholder input, as well as provide new information. Four types of information from the survey are presented in this report: (1) the relative importance of each subtheme, (2) the type of data needed, (3) the spatial scale of the data, and (4) the temporal scale of the data. The relative ranking of the importance of each issue area within each subtheme is presented in fig. 7.2. Because the purpose of the survey was to better understand social science data and research needs, questions were also asked about specific areas of research. For example, within the subtheme of transportation, the most common research topics of interest were (1) transportation choice by tourists, (2) highway use, (3) shuttle bus use, (4) alternative transportation demand, and (5) vehicle miles traveled (VMTs) (see fig. 7.3). Within each subtheme, a series of questions were asked about the type of data required for each topic, and the spatial and temporal scale necessary to make the data useful for professional decisionmaking. Results are presented in this chapter. Respondents

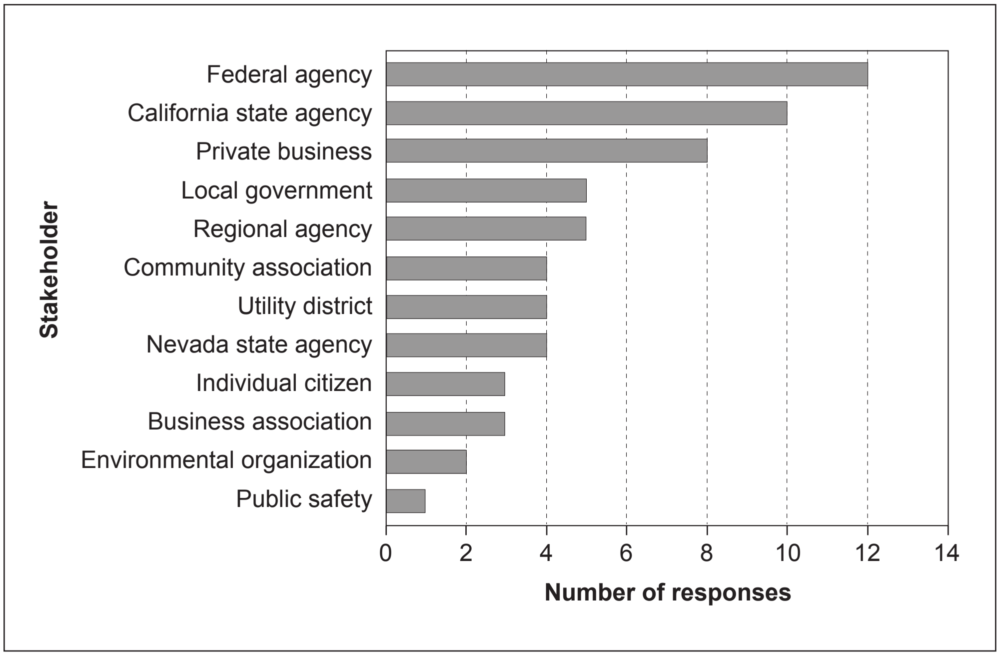

Figure 7.1— Distribution of participating stakeholders by type (n = 61). (Source: Kauneckis and Copeland 2008).

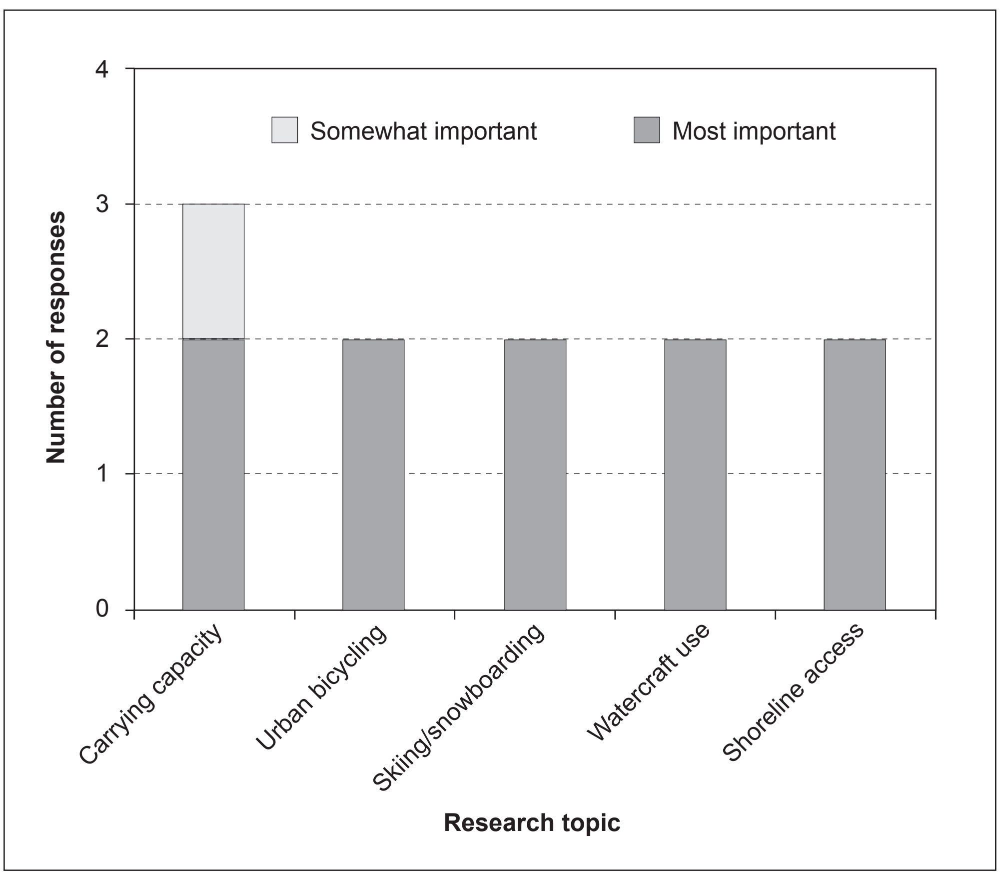

Figure 7.2—Ranked importance of recreation issues (n = 3). (Source: Kauneckis and Copeland 2008).

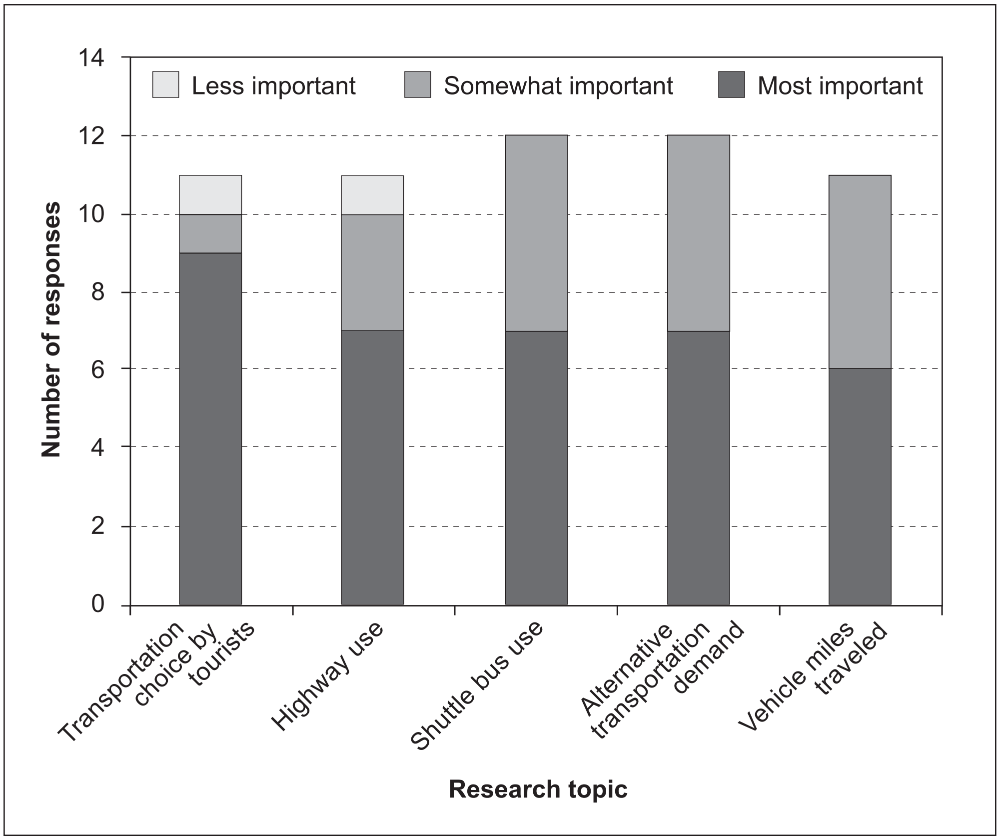

Figure 7.3—Ranked importance of transportation issues (n = 12). (Source: Kauneckis and Copeland 2008).

were given the following list of potential data types along with their definitions: current status—information on current use; future projections—expected future activity; general trends—direction of change; "what-if" scenarios—expected change if a single factor is changed; risk assessment—evaluations of potential risk; efficiency improvements—evaluations of cost effectiveness; alternative futures scenarios—expected change when multiple factors are changed; and online quick reference—single-page dashboard presentation of information. The various spatial scales of social science data were presented as follows: individual—data on individual consumer, citizen, or private landowner behavior; local political jurisdiction—information at county or municipal government level; community—information at aggregate community level (such as South Lake, North Lake, or West Shore); administrative jurisdiction—according to the government agency responsible for an area (such as U.S. Forest Service, utility district, state parks); watershed—information at the natural watershed scale (such as Emerald Bay, Truckee River, Incline Creek); habitat—information at the level of natural habitat area (such as shoreline, forest, grassland); Tahoe basin—information at the level of the entire basin; state—information at the level of state (such as California or Nevada). Finally, in terms of temporal scale, respondents were presented with the following choices: daily, weekly, monthly, seasonally, annually, biannually, every 5 years, every 10 years. Only the most frequent responses are reported here. For the full survey results and methods, see Kauneckis and Copeland (2008).

Because the survey was designed to derive types of information different from that gained in the meetings and workshops, not all of the subthemes have a direct set of equivalent questions in the survey format. This chapter is organized on the subthemes of recreation, transportation, economics, scenic resource, noise, and five cross-cutting metathemes. The survey focused on six areas of social science research: transportation, public agency management, community well-being, economic health, public information and program participation, and recreation. So although information needs on economic activity are consolidated in one heading in this report, the survey attempted to broaden this out to include economic health of the region, various noneconomic aspect of community well-being, and cost-effectiveness of public policies. Similarly, although collaborative information management and policy evaluation are discussed in this report as separate metathemes, in the survey, aspects of public management were combined under public agency management. Survey results would be considered supplemental to those derived from the more focused stakeholder meetings, and both sources of information are complementary in informing social science research needs.

We stress that although the survey presents discrete results, it would be a misinterpretation to accept these as representing the full scope of social science needs, the priority, or even necessarily the key areas of concern by survey participants. The survey is one type of information that should be combined with others to get an accurate picture of priorities. There are important limitations of Web-based survey data collection. The survey was anonymous, and there was no attempt to screen the level of expertise in a specific issue area or the level of management responsibility. Similarly, the intensity of stakeholder preferences was not measured (the ranking does not accurately represent the weight different stakeholders assign to each item). Additionally, the survey was available for a period of 2 months, and some important stakeholders may have not had the opportunity to respond, or may have simply chosen not to respond. There are other limitations common to those familiar with online-survey methods, but the main point is that these results should be taken as evidence of interest and issues to address, not as definitive answers about the needs and priorities of research.

Based on the various sources of information examined, there was an attempt by the authors to prioritize specific research needs. These are presented in table 7.1 along with an explanation of the reasons for prioritization. Items were prioritized based on the following criteria: consistent requests across multiple information sources (publications, stakeholder meetings, and survey data), degree to which a specific item will meet a need identified by the broadest range of stakeholders (public agencies, private organizations and environmental groups), relative ease and costs through which a research priority can meet an immediate management need, and a direct link of social science research to environmental management goals. There was no attempt to reach common agreement on the priority of various research needs among the different stakeholders included in this process. Given the unique nature of questions regarding human behavior, public policy, and economics, and the different interests and management responsibilities of the diverse set of stakeholders, additional work would be recommended to find areas of common research priorities among all relevant stakeholders. The authors are of the opinion that selecting immediate priorities is best left to stakeholders and funding agencies. The priorities given here are intended only to help guide that effort.

A legitimate concern was raised by some stakeholders that by addressing the broad array of social science research questions covered in this chapter, it may distract agency effort away from their central mission of environmental management. Some of the social science issues discussed here may be better left to the private sector and local government rather than natural resource management agencies. However, research conducted during this study indicates there is more overlap between public and private sector interests than may be recognized by stakeholders, and there are multiple issue areas where research effort can be coordinated and conducted with greater collaboration. This chapter is intended to assist in that effort by summarizing the current state of knowledge, suggest some research priorities, and provide a broad framework for discussing future social science research.

Approach

The social science research discussed in this chapter can be arrayed along a continuum of simple data collection and consolidation, to more complex statistical analysis and modeling, and the process of innovation and knowledge production. Specific research topics of interest within each subtheme have been organized to indicate this complexity and placed in one of four general categories of social science research: (1) data collection and consolidation, (2) monitoring for management need, (3) public agency management and collaboration, and (4) policy

Table 7.1—Social science research priorities

Research need	Justification for prioritization
Recreation subtheme:	
Development of consistent, basinwide 3-year recreational survey cycle to track seasonal changes, crowding behavior, and long-term patterns of recreational activity change (R1, R2, and R4)	As the central economic activity of the basin, recreation is of general interest to the public as well as private stakeholders. Additional information on the quality of recreational experience, the factors perceived as increased quality experiences, and information at a basin scale can assist in planning efforts in both the public and private sectors.
Statistical analysis of the factors associated with recreational quality in order to determine visitor preference and direct future infrastructure investment (R5 and R7)	
Analysis of recreational capacity in terms of ecological impact and infrastructure at both the specific site level and basinwide (R8, R9, and R10)	
Transportation subtheme:	
Collection and analysis of current bicycle use data in order to determine road and trail use, and to determine adequacy of current bicycle routes and the potential for use as an alternative transportation mode (T3)	Identified as important information to a broad selection of stakeholders; including the local governments, resource management, and the private sectors. Items outlined here can provide baseline data for other research on public transportation.
Collection and analysis of public transit ridership data to and within basin (T4)	
Centralized collection, inventory and distribution of transportation data at a basin level (T6 and T7)	
Centralized Web-based information source about all basin-level public transportation systems (T8)	
Analysis of effective policy options for addressing parking at high-impact areas (T16)	
Predictive modeling on vehicle use, transit ridership, demographics and linkages between economic health and emergency preparedness (T18, T19, and T20)	
Economics subtheme:	
Increased data collection and analysis of housing trends at the community and basin level (E2 and E5)	There is a strong interest by the private sector in collaborating on core economic data and research questions. Affordable housing, the impacts of the growth of second-home ownership and community-well-being continue to be common issues of interest to basin stakeholders.
Increased data collection and analysis of employment trends at the community and basin level (E3 and E5)	
Increased data collection and analysis of tourism trends at the community and basin level (E4 and E5)	
Estimate affordable housing availability for year-round residents, public sector employees, and workers in service and hospitality industry (E8)	
Evaluation, prioritization, and coordination of Environmental Improvement Program projects (E19)	

Table 7.1—Social science research priorities (continued)

Research need	Justification for prioritization
Economics subtheme (continued):	
Development of community sustainability and well-being indicators (E9)	
Program evaluation of the effectiveness and cost-efficiency of existing policies (E21)	
Analysis of effective policy options for increasing affordable housing options (E22)	
Scenic resources subtheme:	
Examination of public perceptions of the scenic quality of natural and built environments (S3 and S4)	Scenic resources are directly linked to recreational experience. Although of minimal environmental impacts, they are of high importance to individual communities and planning officials. Substantial resources have already been dedicated to outlining management questions and new indicators. Additional research could assist in informing improved policy design.
Development of new Tahoe Regional Planning Agency scenic quality indicators (S4)	
Analysis of effective policy options for increasing building design diversity (S12)	
Analysis of effective policy options for improving overall scenic quality (S13)	
Noise subtheme:	
Increasing spatial and temporal monitoring to capture single-event noise levels (N1)	The research outlined here is relatively easy and directly related to processes already underway.
Research on public acceptability and perception of current noise levels (N2)	
Collaborative information management metatheme:	
Information synthesis and knowledge-sharing about effective approaches for recreation infrastructure, and about mitigating environmental impacts in other alpine resort communities.	Developing a collaborative information sharing network can facilitate data sharing across research areas, act as an information portal for both researchers as well as the public, and is the first step toward decision-support system and complex systems modeling.
Tahoe basin community management metatheme:	
Consolidation of existing information, design of new collection instruments, and examination of methods for upscaling data to the Tahoe basin level and downscaling to the community level.	Research activity needs to be able to address issues at both the basin level as well as local communities. Scaling across spatial units is critical to many of the research issues in this chapter.
Program evaluation, policy design and policy process evaluation metatheme:	
Development of policy conflict resolution mechanisms for programs working at cross purposes. Target research on policy evaluation and program design of costly programs.	Because of the highly regulated environment at Tahoe, evaluation and design issues are important both for the purpose of developing more effective and efficient policy instruments, but also for maintaining public support.

Table 7.1—Social science research priorities (continued)

Research need	Justification for prioritization
Fire and natural hazards metatheme:	
Development of a basinwide emergency communications network, implement reforms to fuels management on private parcels, and begin extensive interagency review of basinwide coordination of fuels management.	If acted on quickly, substantial reforms could be made to public agency processes and private sectors in the basin following the 2007 Angora Fire.
Climate change metatheme:	
Development of predictive models of climate change impacts on the Tahoe environment. Focus on outputs that can communicate potential outcomes to local government, the general public, and agency personnel.	Given the expected impacts of climate change to the Tahoe ecosystem and correspondingly the recreation-based economy, it would be advantageous for planning efforts to be aimed to account for projected climate impacts.

Note: Codes in parentheses reference research needs shown in figure 7.5.

analysis and program design. Data collection issues are the simplest type and involve the use of sampling methods rather than actual research and hypothesis testing. The most commonly identified social science research needs in the basin fell within this category. These tended to revolve around four issues: (1) developing more consistent questions across current data collection efforts, (2) increasing the frequency of collection efforts, (3) up or down scaling existing data to the basin and community level, and (4) expanding data collection to include new emerging management issues. Monitoring for management needs generally falls within the middle range of complexity and involves research directed at commonly identified regulatory and nonregulatory management responsibilities. Research on public agency management and collaboration is slightly more advanced and involves methods of organizational behavior and public management. Most topics mentioned in this area involve ways of increasing interagency cooperation, communication, and coordination of research results, and the development of mechanisms to mitigate perceived policy conflicts. Attention also was directed at improving the relationship between public agencies and the public. Policy analysis and program design included questions on the evaluation of current policies and programs in terms of their effectiveness and efficiency, methods to improve implementation and adoption, and examination of potential new approaches. By organizing according to relative complexity, the framework presents a tool to understand the relative ease by which the various research needs identified here can be achieved, as well as the likelihood that results can be directly incorporated into management decisions. For example, the question of whether visitors are satisfied with the selection of recreational activities available can be answered in a relatively straightforward manner through basic survey research, whereas the question of how climate change is likely to impact recreation is quite complex and involves various projections of probable impacts and estimates of the resulting human choices based on a changing natural environment. Integrating this information into the formal planning process at a basinwide level is one step more complex as it involves multiple organizational units and the policymaking process itself. The social sciences do have methods and techniques that can address each issue, but each requires a different level of commitment and resources by the various stakeholders.

Subthemes are organized according to five topical areas and five cross-cutting metathemes. Across participant groups, the majority of the discussion focused on economics and recreation, with less attention paid to transportation, and only a few stated social science research needs on noise management and scenic resources. This deviates slightly from the ranking of priorities from the survey (fig. 7.4), but not in significant ways given the relatively small sample size and differences in the organization formats.

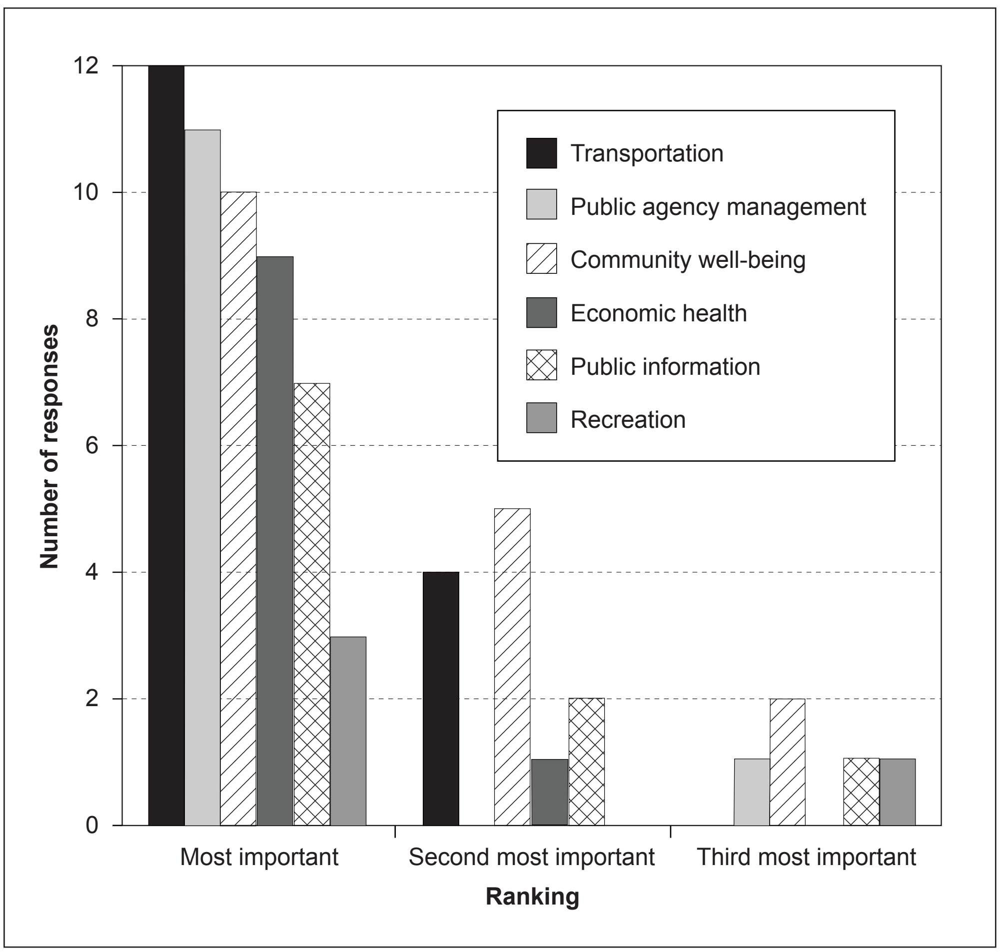

Figure 7.4—Ranked importance of social science research areas (n = 52). (Source: Kauneckis and Copeland 2008).

Conceptual Model

To develop a broad framework of how the social sciences directly impact the natural processes discussed in the other chapters, a conceptual model (fig. 7.5) is used to illustrate relations among the various subthemes and research needs discussed here. The primary drivers of the social processes impacting management at Tahoe involve broad demographic changes and dynamics of the regional economy, both of which are beyond the impact of policy decisions in the Tahoe basin. These influence visitor and resident behavior, generally referred to as choice preferences in the policy literature. Both residents and visitors make decisions regarding such

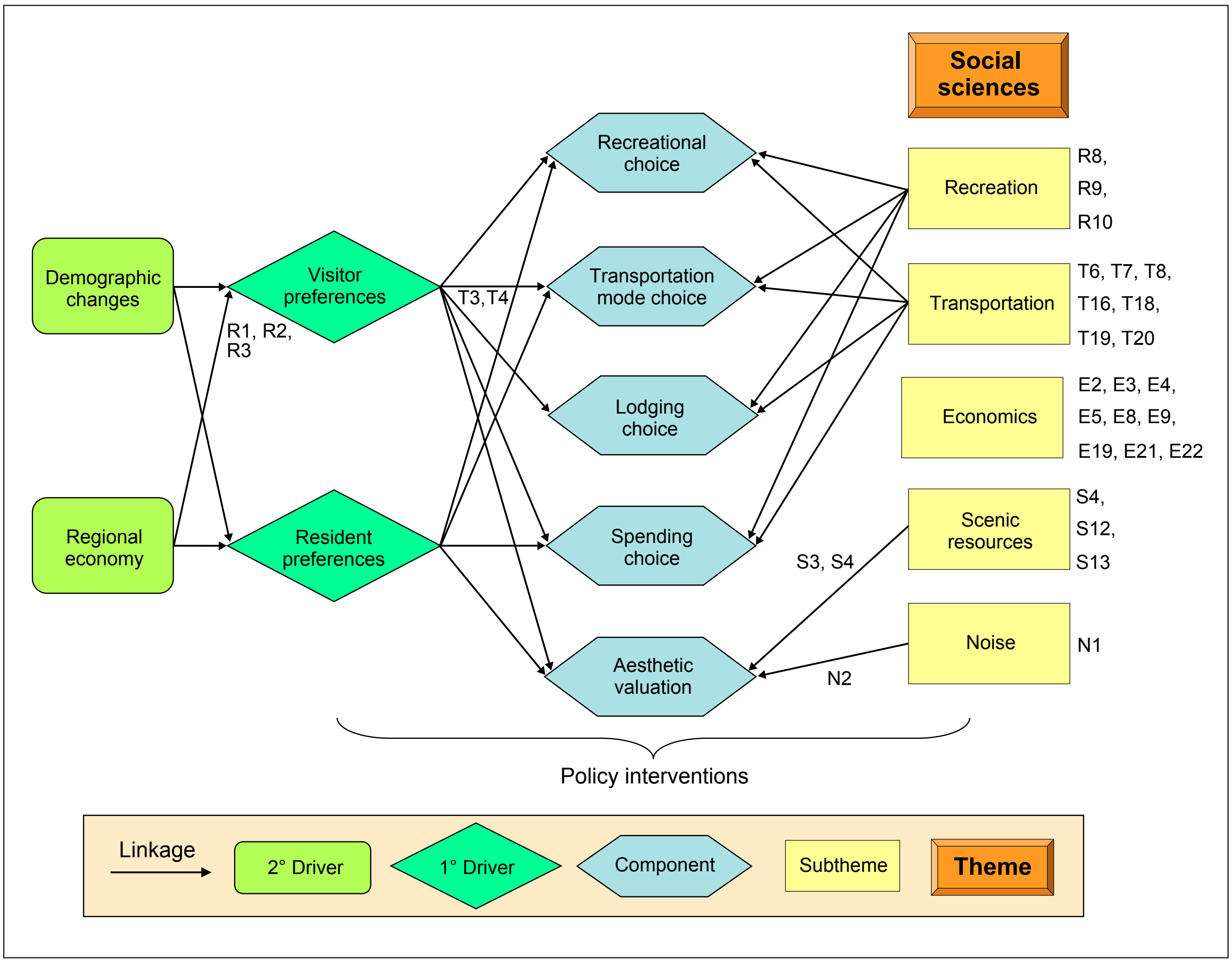

Figure 7.5.—Conceptual model for Lake Tahoe basin social sciences subthemes. Key socioeconomic components are indentified. The arrows indicate how these components are influenced by local and regional drivers as well as conditions and approaches pursued through the various subthemes. The alpha-numeric codes identify the social science research issues considered highest priority (table 7.2). Code locations indicate the conceptual model element that research would most directly influence. Near-term priorities are indicated by alpha numeric symbols (e.g., R1, T3) and correspond to the descriptions presented later in the chapter.

things as recreational activities (e.g., type, frequency, and location), transportation mode (e.g., bicycle, bus, or auto), lodging (e.g., North Shore, South Shore, or a specific hotel), and spending decisions (e.g., location of spending, amount, and item). The subtheme of recreation is impacted by a variety of different decisions, from direct recreational choices to mode of transportation, spending choice, and the aesthetic valuation of recreation sites. There are complex interactions among each of the drivers and subthemes, and the model presented here is a simple representation. Rather than outlining all the potential paths of causality, the figure is intended to illustrate the potential points of potential policy intervention by decisions made within the Tahoe basin. For example, both visitors and residents make transportation mode decisions. There are various types of interventions that can result in incentives or sanctions to influence the choice these two types of publics make. If the goal is to improve parking at specific sites for residents only, allocating parking permits to residents and issuing a threat of fines for those without permits can serve that purpose. Likewise, if increasing ridership on public transportation during periods of peak use is a goal, increasing the availability and frequency of shuttle buses makes that choice more likely. Program activity can also include providing services to account for existing patterns of behavior rather than attempting to change behavior, such as understanding the current demand for alternative transportation modes rather than explicitly attempting to increase ridership. The conceptual model is intended to explicitly outline how a policy or program change can impact the system as a whole.

Recreation

Recreation opportunities by residents and visitors are the driving force of the regional economy. Tahoe contains a wide variety of natural attractions, and tourist amenities. The natural environment provides an exceptional background for a range of multiseason activities. Managing recreation for the estimated 56,000 permanent residents, 200,000 visitors during peak holiday periods, and an estimated 15 million annual visitors—without degradation to the natural environment—presents a number of challenges. Understanding the vulnerability of recreational opportunities to both anthropogenic and natural hazards from such issues as wildfire and climate change, as well as changing consumer and citizen preferences, are important components of the long-term management of the Tahoe basin.


Courtesy of Tahoe Regional Planning Agency

Day use recreation at Sand Harbor State Park, Lake Tahoe, Nevada.

Knowledge Gaps

The most comprehensive source of data on recreational activities are the National Visitor Use Monitoring (NVUM) surveys conducted by the U.S. Forest Service (USFS) with the 2005 report for the Lake Tahoe Basin Management Unit (LTBMU) being the most recent (USDA Forest Service 2006a). A USFS document issued in preparation for a forest plan update noted that recreational visits to the LTBMU have doubled since 1988 to almost 4 million per year (USDA Forest Service 2001). These public surveys are conducted for each management unit within the USFS and are used to estimate visitation as well as activities on USFS lands. Because they are standardized for use across national forest units, they are less useful for Tahoe-specific management questions (USDA Forest Service 2006b).

The TRPA also measures recreation quality at various sites as part of their quintannual Threshold Evaluation Report process. The TRPA measures both the quality of recreation and the amount of recreation provided; the metric for this is a capacity-based system called the Persons-At-One-Time (PAOT) system. It is intended as a planning tool for examining design capacity and the provision of a fair share of recreation for public use. The PAOT works well for closed systems like ski resorts, but not as well for open areas like hiking trails. Nevertheless, PAOT (i.e., recreation capacity) and recreation quality are both indicators of the TRPA recreation threshold. The recreation capacity indicator was attained in 2001, although the recreation quality indicator was not (TRPA 2004b); however, both indicators were attained in 2006 (TRPA 2006a).

The Lake Tahoe Watershed Assessment also contains data on the number of visitors to Tahoe and their recreational activities (Nechodom et al. 2000b). These activities include casino gaming, ski area use, dining, boating, camping, shopping, and hiking. Transportation data collected by the TRPA also contain useful information on recreational activities involving destination points. The various business organizations in the basin also use private consultant studies to collect data on specific recreational activities, spending, and the tourism market (e.g., Nozicka 2001, 2003; NuStats 2004). Much of this has been shared and published in various public reports, but to our knowledge, there has not yet been a full inventory and analysis of existing data. The Pathway planning process has begun the process of establishing new metrics and standards by developing new indicators to measure recreation quality, access, and education. These are still under refinement and discussion (Design Workshop Incorporated 2004).

Research Needs

Fourteen areas of potential research were identified for the recreation subtheme in the tabulation on page 306. These are categorized into three areas of research: data collection and consolidation, monitoring for management need, and public agency management and collaboration. Data collection and consolidation issues included requests for increased consistency and consolidation of data toward understanding trends in recreational activity across the entire basin (indicated by R1, R2, and R4 in the tabulation on page 306). Current data collection is focused on specific agency needs, and no agency is gathering adequate data for basinwide planning. Specific items discussed include more complete, frequent, and consistent surveys of recreational quality and access, recreational area usage, occupancy rates in various types of tourist accommodation units (motels, campgrounds, rented cabins), and demographic data about who partakes in various types of recreational activities and where. The TRPA has requested a 3-year cycle of surveys wherein winter recreation users are surveyed one year, summer recreation users the next, and the third year would be used for special “focus surveys” targeted to specific questions or issues (R2). It also is critical to detect differences between visitor and resident populations’ opinions about recreational experiences, and usage patterns. This includes one of the most requested items, the development of a core set of survey questions to be included in all surveys conducted within the basin regardless of their specific purpose (R1). This standardization of questionnaire data would allow for a more complete picture of general information (e.g., demographics, origin, destination, and travel cost) over a longer period and at a broader scale than what is currently collected (R4). This would enable better trend analysis and the ability to develop predictive models. Because surveys are conducted for different purposes, each survey can still have a section specific to those needs, but a subsection could be standardized. Better information is needed specifically for the capacities of open and closed recreation areas for planning parking and public transit opportunities across the basin (R4). Finally, some importance was placed on tracking accomplishments like miles of new trails or trailheads and the amount of shoreline available for public recreation (R3).

The second aspect of recreation research was characterized as issues involving specific monitoring for management need (R5–R12). There is a perceived need to go beyond simply monitoring use of recreation areas, toward understanding the environmental impacts of various types of recreation in locations with differing sensitivities (R8). For example, there is a perception that there has been a decrease in low-impact recreational activities (such as snowshoeing and hiking) and an increase in high-impact activities (such as snowmobiling and mountain biking). It would be useful to determine the different impacts of a single day of peak usage versus many days of high nonpeak usage. A very common discussion point was on exploring ways of balancing conflicting recreational use demands (R10). The potential conflicts between protecting fragile environments while providing high-quality recreational opportunities warrants research to determine the tradeoffs and means of mitigating negative impacts. Some stakeholders expressed the importance of capturing unmet demand. They wanted to know who did not participate in various recreational activities at Tahoe and why. Were they priced out, crowded out, unable to access the recreation facility, or was there some other reason (R10)?

The types of research questions presented above include statistical analysis of the factors associated with current measures toward developing a better understanding of what factors increase recreational satisfaction and how well current indicators capture the relevant management questions (R6, R7, and R8). Examples include identifying a system for capacity planning that could augment or replace the PAOT system. Specific topics for capacity-related research were parking, access, facilities, and transportation to and from the recreation areas. For example, would it be an effective strategy to design the capacities (parking, in this case) of natural recreation areas to accommodate average demand, and then augment that with free public transit on peak demand days? It was suggested that effort be made to understand the capacity differences (available and needed) between peak demand and average demand, as well as how to choose accompanying facility designs (R9 and R10). The USFS, in particular, requested research and modeling of recreation capacity throughout the entire basin, with an emphasis on South Shore recreation areas (R7). Example research topics included the status and trends related to visitor use, visitor experience, and visitor preference on national forest lands within the Lake Tahoe basin. A study exploring the relationship between recreation capacity and recreation experience also was of particular importance to the USFS. Another proposed topic of research is the quantification of "high-quality recreational experiences" (a TRPA regulatory threshold and a major goal of the USFS and other organizations participating in the Pathway planning process) through statistical analysis of survey responses with particular quantifiable conditions in that recreation area (e.g., amount of crowding, restroom availability, interpretative signs, parking spaces, and other elements of facility design). From such analysis, predictive modeling could be completed to quantify the likely recreation experience without having to rely directly on survey responses. This type of research also included new areas of crosscutting research such as the vulnerability and resilience of tourism to natural hazards and climate change (R11 and R12), which are further discussed as crosscutting metathemes below.

The third most discussed area for social science research was the creation of a data clearinghouse or other system whereby survey results related to recreation could be better distributed to a wider variety of organizations (R11). The need for communicating information to citizens was highlighted in transportation and access to recreational areas, particularly during periods of peak use for heavily impacted areas. The dissemination of information on what other recreational communities have done to manage similar problems is another use of a data clearinghouse discussed among stakeholders (R12). The section below on "Collaborative Information Management" elaborates further on the potential uses of a data clearinghouse. Results from the survey serve to highlight some specific areas of interest; although it should be kept in mind that there were very few respondents, many respondents' likely subsumed recreational areas of interest into community well-being and economic health.

Table 7.2 illustrates the relative importance of the top five interest areas for recreation. All five issue areas were ranked the same in terms of overall importance, with the development of an indicator of carrying capacity for recreational use having the highest overall level of interest. The other areas of interest included measurement of bicycle use on trails in urban areas, skiing/snowboarding activity, watercraft use, and shoreline access. Table 7.2 presents the preferred type and format of the data. In terms of data to be collected, the majority of respondents were

Table 7.2—Recreation information

	Recreation	Carrying capacity	Urban bicycling	Skiing/ snowboarding	Watercraft use	Shoreline access
				Number of responses		
Type	General trends	**1**	0	0	0	**1**
	What-if scenarios	**1**	0	**1**	0	0
	Efficiency improvements	**2**	0	0	1	0
Spatial	Local political jurisdiction	**1**	0	**1**	**1**	0
	Administrative jurisdiction	**1**	**1**	0	0	1
	Tahoe basin	**1**	**1**	**1**	0	1
Temporal	Daily	0	0	0	**1**	**1**
	Seasonally	0	0	1	0	0
	Annually	**3**	1	1	1	1

Note: Items in bold represent the most frequent responses in each row.

interested in recreation carrying capacity and improvements in the efficiency of recreational offerings. Recreational carrying capacity is an important issue for both public and private sector interests as it impacts the use of public lands, associated public infrastructure such as parking and transportation, and the regional economy. Carrying capacity includes two aspects; the ability of infrastructure to meet public demands, and the environmental impact of recreational activities. There was a diversity of spatial extents of interest. Research on urban bicycling, skiing/snow-boarding, and shoreline access was of interest at the basin level. Annual collection of data was consistently the temporal scale of interest across all recreation issues.

Transportation

The movement of people, goods, and services is an important component of the Tahoe economy and community. Creating appropriate infrastructure and mitigating the negative environmental impacts of transportation is one of the most challenging issues in the basin. Transportation issues include improving travel times for residents and visitors to the basin, reducing congestion, air pollutant emissions, runoff from road surfaces, operations and maintenance of impervious surfaces, and risk of accidents. The transportation subtheme focuses on the social science needed to understand specific patterns and modes of transportation, and their interaction with employment, recreation, and other aspects of environmental, economic, and community health. Motor vehicle transportation does generate air and water pollution, and the physical processes are described in the "Air Quality" and "Water Quality" chapters of this science plan. This section focuses on the behavioral aspects of transportation.

Knowledge Gaps

The major aspects of socioeconomic interest with regard to transportation are VMT and alternatives to private vehicle use. Also of concern are travel patterns and congestion-related delays, typically measured in vehicle-hours of delay (VHD). Lake Tahoe transportation planning is done partly by the TRPA, which has certain transportation planning responsibilities, and by the Tahoe Metropolitan Planning Organization (TMPO), which is primarily responsible for federal transportation planning. The TRPA and TMPO goals are to maintain environmental protections, plan for growth in the major population centers, and ultimately support the economic vitality of the basin. Obtaining these goals would require a functional multimodal transportation system including roads, bicycle and pedestrian paths, public transit options, and reduced traffic congestion.

The TRPA has a goal of reducing VMT by 10 percent relative to the 1981 levels, a target that has never been met. The VMT has actually increased by somewhere between 3 percent (TIIMS 2006) and 8 percent (TRPA 2004a) in the last 20 years. These rates of increase are in line with the basin's rate of population growth, but much lower than surrounding communities in California and Nevada. Growth of both human population and VMT in the Tahoe basin are constrained by limits on additional housing and roads. Despite the small increase in VMT, peak traffic volume seems to have leveled off or even declined since 1981 (TRPA 2008). The TRPA and the California Department of Transportation measure peak traffic volumes on the U.S. 50 corridor as part of their ongoing program of traffic counts. The VMT is not directly measured but rather modeled based on a program of traffic counting using both automatic permanent counters and spot counts.

The 2004 Regional Transportation Plan provides much of the available data on VMT, origin/destination, occupancy, and public transit ridership (TRPA 2004a). It also discusses those EIP that are currently underway, planned, and funded that address transportation concerns. Other sources of information are contained in the Threshold Evaluation Reports issued by TRPA every 5 years and consultant reports (see LSC Transportation Consultants 2003, 2004, 2005; Tahoe Regional Planning Agency 2008). NuStats consulting has recently conducted intercept surveys at specific locations to gather origin-destination and other data necessary for TRPA's transportation planning purposes (NuStat 2004), but nearly 30 years has passed since the same set of information was collected,[5] and some business leaders have expressed concerns about the methods and its use. A common source of tension

[5] Norberg, Keith. 2006. Personal communication. Senior planner, Transportation Department, Tahoe Regional Planning Agency (TRPA), 128 Market Street, Stateline, NV 89449.

between business and transportation planners is that a reduction in the availability of common transportation modes (typically automobiles and associated parking) may restrict economic activity. Finding the correct balance is an ongoing process.

Although there are no regulatory threshold standards for transportation, there are air quality thresholds that rely on VMT and U.S. 50 traffic volume. As a result of the Pathway planning process, a revised set of transportation indicators were presented to the TRPA governing board for approval. These proposals include an emphasis on multimodal transportation systems, viable alternatives to private automobiles (i.e., public transit that is accessible and useful to a wide range of people), and the replacement of VMT with an environmental vehicle impact indicator. If adopted, assessing the status of these proposed indicators would obviously require specific monitoring efforts (TRPA 2006c, 2006d), and these needs are discussed in the research needs section below.

The TRPA has recently replaced its transportation planning model, TRANPLAN, with another modeling software tool called TransCAD, which is being parameterized by Parsons-Brinckerhoff, Inc. The inputs are numbers and locations of occupied homes, number of workers and jobs, and travel origin and destination information for residents and visitors. The outputs are total VMT, overall delay, and alternative transportation mode splits (TRPA 2008).

Courtesy of Tahoe Regional Planning Agency

Tahoe Trolley, a seasonal public transport service running between the north and south ends of Lake Tahoe.

Although 90 percent of Tahoe visitors arrive by private vehicle and most local residents own and regularly use cars, there is a large network of public transit options, including BlueGo, the Tahoe Area Regional Transit system, the Tahoe Trolley, and private ski area shuttle buses. Ridership numbers and both temporal and spatial use patterns are available from these systems, although they have not been consolidated into a central reporting location. Overall, the network appears to be underutilized, but with "spiky" high levels of use in certain locations and periods. A system of bicycle and pedestrian paths for both recreational and transportation use exists in portions of the basin, but it is spatially incomplete enough that it does not provide a completely motor-vehicle-free experience. Finally, there are some watercraft-based transit options, including the Tahoe Queen, which ferries passengers—primarily skiers—between the north and south shores during part of the ski season, and a limited water taxi service that operates along the south shore during the summer months. There is interest in exploring expanded ferry use to mitigate congestion during other seasons.

Research Needs

Twenty areas for potential research were identified for transportation (tabulation on page 307). These were categorized into three areas of research effort: data collection and consolidation, public agency management and collaboration, and program analysis and policy design. The issue of data collection and consolidation duplicates many of the same issues in other sections, with general needs for increased volume, consistency, and replication of transportation data (T1–T5). Enhanced monitoring efforts were recommended with increased spatial and temporal coverage (T1). Data of interest included traffic counts, vehicle occupancy, origin-destination, trip purpose, number of trips per day, and others. Management agencies have stated that the base data on these topics are so spotty that there is no basinwide consensus on whether traffic volume and congestion are increasing, flat, or decreasing in recent years. Specific areas of interest include data on bicycle use on both paved and unpaved trails, in bicycle lanes, purpose of use (commute vs. recreation), miles ridden, origin-destination, and hours spent riding (T3). For mountain bike trails, interest was expressed in knowing whether people drove their cars or rode their bicycle to the trailhead. The Tahoe City Public Utility District has regularly surveyed users on its multiuse trail network over a number of years, and the methodology may serve as a model for the basin (Tahoe City Public Utility District 2007). More detailed and integrated data about public transit ridership could better inform transit operations. Particularly important would be the numbers, demographics, and transportation choices of basin visitors who did not arrive in private vehicles. Just as important is the use of public transit to get to recreation areas or commercial cores. Better monitoring of congestion and VHD would be useful to the TRPA, as very little of that information is regularly collected (T2). It also was suggested that a metric of "person-hours of delay" be developed to include the delays experienced by people riding buses (T9).

An important addition to the collection of transportation patterns is detailed demographic information of who is going where and for what purpose, and linking this to statistical analysis of behavior (T10). Knowing the interactions between demographics and travel patterns would increase the utility of the information for general planning purposes. Similarly, it would be useful to know the differences in transportation patterns between day-use visitors, overnight visitors, and residents, especially with regard to their travel to recreation areas and commercial core areas. Collecting and analyzing these kinds of data on regular intervals is critical for presenting overall trends.

The TRPA's transportation models indicate that many of the traffic problems have stabilized or even decreased in recent years (see footnote 5), and yet prevailing public opinion is that things continue to worsen. Research into the source of these perceptions was considered useful to the TRPA and other organizations to determine to what degree this represents specific transportation infrastructure problems or just changing aesthetic values (T5). Particularly important was research to guide the development of a Transportation Environmental Impact Indicator, should it be approved. This would relate vehicle impacts directly to goals for water and air quality, wildlife, noise, and other resource areas (T7).

As with other sections, there was substantial discussion about improving interagency collaboration and developing a basinwide information infrastructure (T6–T8). It is possible that much more data exist than is acknowledged here, but there is no centralized collection, inventory, or distribution of that information. A research step of primary importance would be to review all available studies and planning documents for the purpose of compiling existing data and identifying and filling data gaps (T7). A centralized Web site with information about all public transit systems and options including route, fare, and ridership data would be tremendously useful. Broad support for this information distribution system came from both the business community and planning agencies (T8).

Many of the research issues were directly related to addressing specific questions of program analysis and policy design (T9–T20). The types of questions included determining how people and their travel behavior would respond to changes in prices of parking or gasoline, special vehicle use fees, increased or decreased congestion, mandatory public transit to certain heavily visited destinations, and incentives to ride public transit and rideshare (T15, T16, and T17). There was discussion of the importance of understanding the linkages between transportation, recreation, land use, and population, as well as how transportation affects social, economic, and equity issues (T18). Feasibility studies of many different transportation and transit options were recommended to understand the effectiveness of various types of incentives or disincentives. There is also interest in understanding the intra- vs. interbasin traffic trends and effects on travel dynamics of job locations (T18). The trend toward second-home ownership has important impacts on transportation planning as fewer year-round residents are present (T13). Some participants requested studies of how these trends affect Tahoe basin town centers and common areas; whereas others were concerned about the impact on transit options for low-income workers (T14 and T18).

Specific studies of what it would take to increase transit ridership and reduce private vehicle use also were discussed (T15). One example given was to explore the feasibility of a commuter bus into the South Shore area from the communities of Minden and Gardnerville. Another was to study the demand and feasibility of a ferry across Lake Tahoe (T11). Currently, the approach is to increase transit options, and although many stakeholders want and value increased public transit, there has been little research done to establish the consumer demand or willingness-to-pay for public transit or the intermodal transit hubs that could accompany them. Research on the most important destinations (commercial and recreation), key locations for transfer nodes, and similar information would enable transit operations to be tailored to increase total ridership.

Parking restrictions and enforcement of violations are contentious issues in the basin. Access to recreational facilities is limited by parking capacity, yet many park illegally to access the area (Franz and Nozicka 2003). This has negative effects on the recreation destination, but it also leads to overuse and congestion on transportation corridors and to direct impacts on air quality and water quality and degradation of soil and vegetation. Research into the proper balance between increasing parking capacities, raising fees, and enforcing restrictions would benefit local communities and law enforcement, which are often at odds about this topic (T16).

The vulnerability and resilience to natural hazards (including large forest fires, earthquakes, earthquake-triggered seiche waves, and landslides) of the roads and other transportation systems in the Tahoe basin would benefit from further study both in terms of public safety and infrastructure vulnerability (T19). Finally, management would benefit from predictive modeling based on the data and insights described above: insights about long-term dynamics in vehicle use, transit ridership, or population demographics would all improve the ability to plan for transportation infrastructure needs farther down the road (T20).

The stakeholder survey gives additional insight into the need for transportation research. Survey results (table 7.3) suggest the most important research issue is alternative transportation demand. Similar in priority were transportation mode choice by tourists, highway use, shuttle bus use, and VMT. Highway use statistics were considered of particular concern to the business community as there was a desire to distinguish destination traffic to Tahoe from that of nondestination highway traffic.

Table 7.3—Transportation information

	Transportation	Transportation choice by tourists	Highway use	Shuttle bus use	Alternative transportation demand	Vehicle miles traveled
		Number of responses				
Type	Current status	6	6	6	**8**	6
	Future projections	**7**	6	6	**7**	**7**
	What-if scenarios	5	4	4	**6**	4
Spatial	Local political jurisdiction	**3**	**3**	2	2	3
	Community level	**3**	**3**	**3**	**3**	**3**
	Tahoe basin	3	**4**	3	3	3
Temporal	Seasonally	**4**	3	**4**	2	3
	Annually	2	**3**	2	2	2
	Biannually	1	1	**2**	**2**	1

Note: Items in bold represent the most frequent responses in each row.

The most important types of data for transportation were current status and future projections (table 7.3). General trends and various forms of scenario analysis were of equal frequency depending on the specific transportation issue. Table 7.3 shows the spatial extent of concern—the Tahoe basin, community level, and local political jurisdiction—in about that order. Unsurprisingly, the temporal range for collecting transportation data across issues was seasonal, with some interest in annual data for highway use and alternative transportation demand.

Economics

For the purpose of this chapter, economics was defined as the management, use, allocation, and flow of fiscal resources. It includes aspects of the broad regional economy as well as that of specific sectors and allocation of resources among public and private organizations. Although direct interventions in the private economy

Peter Goin

Local businesses, east side of Highway 50, South Lake Tahoe, California.

should always be approached with caution, indirect impacts in terms of reducing negative externalities, producing public goods, understanding the impact of regulations, and managing the public economy are important areas of management concern.

Because economics is explicitly one-third of the “Triple Bottom Line” concept (i.e., environment, economy, and community)—and is a major part of another third (i.e., human communities)—it is not surprising that this subtheme dominated many of the workshops, symposium breakout sessions, and literature reviews. The “Triple Bottom Line” and other sustainability framework concepts arose out of the recognition that environmental management is inextricably linked with human economies and communities, and is appropriately considered in comprehensive planning strategies such as the Pathway planning process. Within the private sector, information on sector-specific economic trends can assist in improving the sustainability and competitiveness of the business community, aid in short- and long-term planning, help in developing new markets, and help in adjusting to broad demographic changes. Based on recent activity by the Chambers of Commerce, there is substantial overlap in the information demands of public and private sector organizations in the Tahoe basin.

Knowledge Gaps

There have been a number of recent attempts to identify what is known about economic activities, trends, and sensitivities at Lake Tahoe. Nechodom et al. (2000b) provided status data on the population, demographics, spending, and visitation at Lake Tahoe. However, they noted that "the broad and inconsistent range of socioeconomic data that does exist has been gathered in a piecemeal fashion, funded by the private sector or by public agencies whose missions are to support tourism and recreation." They noted that little baseline socioeconomic information is available beyond non-Tahoe specific county-level data. Other reliable information comes from the California Employment Development Department; the Nevada Departments of Employment, Transportation, and Rehabilitation; other state agencies like the Nevada Gaming Control Board; industry groups like the Reno/Sparks Convention and Visitors Authority or the California Ski Industry Association.

The TRPA releases Threshold Evaluations Reports every 5 years, which contain some information about employment and earnings distributions and housing stocks. Although socioeconomics is not one of their regulatory thresholds, various aspects are monitored as indicators of social and economic well-being (TRPA 2001a). An Affordable Housing Needs Assessment was conducted in 1997, not repeated since, which showed that 77 percent of basin employees fell into the low or very low income categories (Tahoe Regional Planning Association 1997). The Regional Travel Impact Model (RTIM) developed for the TRPA, focuses on the impacts of visitor spending both for the Lake Tahoe basin and the Greater Lake Tahoe area (which includes the city of Truckee, and ski resorts and recreational areas just outside the Tahoe basin). The RTIM model was used in the visitor spending analysis for TRPA's 2001 Threshold Evaluation Report to provide greater detail on visitor spending by visitor type and specific activities. The direct economic impacts associated with visitor spending were generated using RTIM, but were again one-time results, not trends (TRPA 2001a).

The USFS typically conducts NVUM surveys every 5 years. These surveys gather the demographics, activities, and spending data of forest visitors, but are designed for managing recreation, not for collecting economic data. The Pathway planning process draft documents set out proposed desired future conditions and proposed indicators to measure them. As part of the Pathway process, a series of place-based visioning workshops were conducted in each community around Lake Tahoe in the summer of 2006 (Regional Planning Partners 2006). The aggregated vision statements from these group discussions are available online (http://www.regionalplanningpartners.com). In addition to these Tahoe-specific efforts, county- and state-level data, as well as national census information can be brought to bear on understanding economic trends in the basin, with various levels of difficulty involved in scaling it to Tahoe-specific aspects.

The economic and community health of Tahoe communities has also begun to be discussed as an important research need. Recent work conducted by the U.S. Army Corps of Engineers in connection with the North and South Lake Tahoe Chambers of Commerce has produced a working document outlining data collection needs for developing a set of "community sustainability indicators" that focus specifically on the human environment (U.S. Army Corps of Engineers 2008). The set of 73 initial indicators was reduced to a subset of 13 measurements deemed the most feasible and cost-effective for pursuing. The selection process used and method of prioritization provides an important model to build on for other social science research. These 13 measurements were considered in the social science priorities outlined here. Based on all of these information sources, a number of key insights emerge.

First, there is a perception that the trend toward increasing second home ownership and decreased year-round residency has serious implications for the economic viability and community character of Tahoe. The declining school enrollments have been read as a loss of families living in the basin. As in much of the country, housing prices have escalated dramatically at Tahoe. A nearly-fixed stock of housing units combined with a trend toward second homes has led to a shortage of affordable housing as less of the housing stock is available for year-round residents. Further, environmental regulations limit the ease with which additional housing can be built for lower income residents. These types of lower income workers are an important population to consider because most employment and earnings are in the service and hospitality industries. Recreation and tourism drive the local economy.

Research Needs

Twenty-two areas of research were identified for the economic subtheme (see tabulation on page 308). These are discussed in terms of the four general categories of research used in earlier sections: data collection and consolidation, research related to specific management needs, collaborative research across organizations, and program evaluation and policy design. As with the other sections, the greatest demand was in the area of basic data collection and consolidation (E1–E9). There is a need for more standardized and regularly collected data about three main topics: housing (E2), employment (E3), and tourism (E4). Given the trends toward second-home ownership, the high cost of housing for either purchase or rent, and the difficulty of adding to the housing stock, it is important to obtain the following information in more detail and at more frequent intervals: the stocks, locations, and prices of various housing types; the numbers of full- and part-time residents; home sales figures including time-on-market and unsold inventory; number of rental properties occupied and vacant; rental rates; turnover rates of commercial and residential properties; percentage of residents who own their homes; percentage of local workers who reside in the basin; number of occupants in a residence; percentage of homes with children (and their school enrollment); percentage of median income spent on housing; percentage of households that can afford a median priced home; living conditions of low-wage earners, and assessed values/property taxes. For all of these topics, it is critical to develop estimates of the historical trends to provide the ability to project future dynamics. Some stakeholders noted that a formal and complete housing assessment, at 5-year intervals, could collect this data in a consistent manner, although others said this is akin to a local version of what the U.S. Census Bureau already does and is therefore too large an effort to conduct locally every 5 years. Further, a number of different stakeholders expressed interest in knowing how many of the current public servants (e.g., police officers, firefighters, teachers, and government employees) are able to live in the basin (E8).

With regard to employment (E3), the development of status and trends data is recommended for earnings and employment distribution, number and type of jobs, permanent vs. seasonal dynamics, place of residence of workers, poverty rates, health-insured households, the number of mid-sized businesses (10 to 25 employees), business startups and closures, and numbers of sole proprietorships (especially run out of a home). As for tourism and visitation (E4), more regular and consistent collection of community-specific data such as the number of hotel nights, total transient-occupancy tax (TOT) receipts, means of arrival and transportation around the basin, duration of stay, campground use vs. hotel stays vs. cabin rentals, the amount of uncollected TOT from cabin rentals, what activities tourists engage in and how much they spend on them are some of the data that was requested.

Community well-being indicators are included in this section as they tend to have substantial overlap with economic research needs. Survey results for this subtheme are discussed below. Many community workshop participants requested—and the proposed revised TRPA indicators would require—tracking and reporting of school enrollment, arts funding, local donation ratios (E5), and number of business/construction permits, and permitting cost distributions (E1). Interest also was expressed in understanding the socioeconomic situation of specific populations living and working in the Tahoe basin, including low-income workers, Latino populations, and Washoe tribe members (E7). Generally, this kind of information included aspects of both community well-being and interactions with other broader areas of concern such as housing, service and tourism industry employment, tax base, and transportation (E11). A number of organizations also requested developing alternative methods of measuring economic and social well-being (E9). The Sierra Business Council developed a metric called the "Wealth Index" that includes common economic factors along with social indicators like literacy, health care, and others (Sierra Business Council 2006). There were discussions that a similar index could be developed for the Tahoe basin. This idea has moved forward in terms of the recently presented Community Sustainability Indicators (U.S. Army Corps of Engineers 2008).

Research topics related to specific management needs include an array of questions having to do with the impact of changing conditions on the basin economy (E10–E15). Topics generally revolved around understanding the elasticity (marginal change) of demand for various activities, goods, and services. This would inform decisionmakers about the expected changes in visitation, spending, home ownership, employment levels, commercial or residential rents, that might result from a change in one or more of the conditions affecting them (E10, E11, and E13). For example, how susceptible are tourism levels to changes in hotel rates or ski lift tickets? At what level of rental home increase will seasonal workers stop seeking work at Tahoe? What will be the change in property values if the air quality (visibility) or lake clarity degrades? There are a number of methods common in social science research for generating objective evidence on such questions.

A number of parties were interested in economic "leakage" of basin revenue to communities outside of the Tahoe basin. This includes workers taking their wages to homes located elsewhere, or to locals spending their income in stores in Carson City, for example. These dynamics seem to exist but have not been measured, and may provide an economic justification for expanding affordable housing in the region (E11). There also was interest in the economic impacts of special events like festivals, triathlons, or concerts (E11) and the competitiveness of Tahoe-based businesses (E12). Others mentioned broader studies on the impact of regulations on the regional economy and determinations of the marginal benefit of additional environmental quality gains (E13). This is probably the most difficult research need as it involves very complex economic interactions (discussed further below). Other complex research questions were also expressed, such as the impact of climate change and natural hazards on visitation, employment opportunities, housing values and prices, business activity, ski resort use, hotel room rentals, and the overall Tahoe economy (E14, E15). Predictive modeling and forecasting, the logical progression of many of these research efforts, might be developed to project housing prices, jobs and wages, or visitation responses to guide policy decisions more accurately (E13).

One example is projecting how redevelopment would proceed given certain incentives and market conditions (E10). Although simulations of this sort are relatively complex tasks, often producing highly uncertain results, some types of simulation modeling might produce useful information and the concept is worth exploring.

As with the other subthemes, a broad crosscutting topic was the potential for collaborative research across organizations (E16, E17, and E18). Much of the primary data are already collected periodically by various entities—the counties, the school districts, the chambers of commerce—but there is no systematic way of accessing or sharing data. The most thorough survey of existing economic data was recently conducted as part of the Community Sustainability Indicators study (U.S. Army Corps of Engineers 2008). A data clearinghouse would be particularly useful in this case, where so much of the information needed could be gathered and shared quite easily (E16). The utility of a "library" or database of land/property market valuation studies for other communities similar to Tahoe also was discussed as a component of such a clearinghouse (E18). Collaborative funding, collecting, and sharing of data will allow much more of it to be gathered at lower cost, and coordinating research efforts will allow for academic or government researchers to direct their efforts more efficiently toward needed research topics (E17).

The last category of research questions involves issues of program evaluation and policy design (E19–E22). Additional research and more extensive application of policy analysis tools were broadly included under economic research. This included consistent methods and practices for evaluating, coordinating, and prioritizing EIP projects (E19) in order to implement the projects with the greatest marginal effect first. This also included developing an implementation framework for tracking, auditing, and quantifying the benefits of various projects to maintain ongoing funding as well as broad public support. A frequently voiced concern was how to provide incentives to encourage or discourage certain behaviors. Specific research topics included understanding and quantifying incentives to increase compliance with best management practice (BMP) requirements on private lands, stimulate redevelopment of commercial or residential properties, leverage public and private investment in community spaces and green building construction (E21), provide low- and moderate-income housing (E22), slow the trend toward second-home ownership, and retain businesses in the Tahoe basin. Other research topics included studying the feasibility of trading systems for air or water pollution emissions and the expansion of land coverage "banking" systems (E20). Affordable housing issues were mentioned in this section as well as determining what housing bonuses would be needed to keep teachers or firefighters living in Tahoe communities (E22).

Overall, a number of stakeholders expressed a desire for establishing a consensus vision—or a process to establish one—for identifying and managing economic goals and ongoing monitoring of the community's social and economic well-being.

The survey of social science data needs helps to narrow the focus of this broad array of issues. The three most important items of interests were housing affordability, the economic impact of different types of visitors, and gaining access to information on similar resort economies. This was followed by redevelopment investment and general visitor profile/behavior information (fig. 7.6).

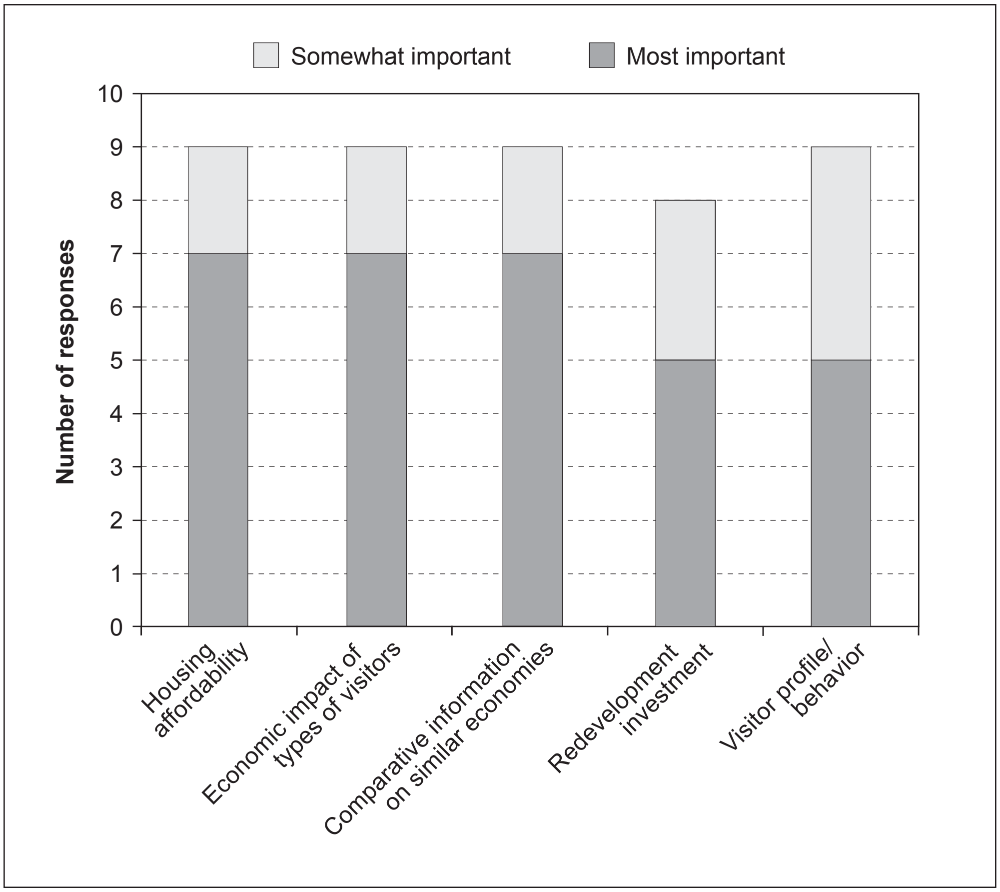

Figure 7.6—Current source of social science information (n = 50). (Source: Kauneckis and Copeland 2008).

The types of information requested differed according to the specific research areas (table 7.4). The most important housing affordability information was on current status and alternative futures (projections of alternative scenarios), followed by general trends. Types of information on the economic impact of visitors included general trends, current status (interpreted as more information about the economic

Table 7.4—Economics Information

	Economic	Housing affordability	Redevelopment investment	Visitor profile/ behavior	Economic impact of visitors	Comparative information
				Number of responses		
Type	Current status	3	3	3	**4**	**4**
	General trends	1	3	**5**	**5**	**5**
	Alternative futures	3	2	2	2	**4**
Spatial	Local political jurisdiction	2	**4**	3	**4**	**4**
	Community level	**4**	**4**	2	3	2
	Tahoe basin	2	1	3	2	**5**
Temporal	Seasonally	2	0	**3**	**3**	**3**
	Annually	4	**3**	3	**4**	**4**
	Every 5 years	0	**3**	0	0	1

Note: Items in bold represent the most frequent responses in each row.

impact of current visitation), and alternative futures. Information types on comparative information on similar resort communities included general trends, and current trends and alternative futures ranked equally.

The spatial extent of data was focused on community level for housing affordability, local political jurisdiction for the economic impact of visitors, and local political jurisdiction and the Tahoe basin for comparative data on other resort communities. The temporal extent was generally annual and seasonal.

Scenic Resources

There are a number of aspects to the management of visual resources and the scenic characteristics of the Tahoe basin. Views of, and from the lake, aspects of the built environment, and forest appearance all contribute to the overall scenic quality. Scenic quality directly impacts property values and underlies the choice of recreational activity within the basin as well as in choosing the basin as an overall travel destination. Important aspects of scenic quality are covered in other parts of this science plan, and are not directly discussed in this chapter. For example the issue of visibility loss because of air pollution is covered in the "Air Quality" chapter; and lake clarity, in the "Water Quality" chapter. It should be noted that the single greatest threat to basin scenic resources is a catastrophic forest fire, a topic considered in several other chapters of this science plan. However, the question of the social acceptance of various treatment options for forest fire fuels is relevant to this section and is discussed below and in the natural hazards metatheme.

Jim Markle

Emerald Bay, Lake Tahoe, in autumn.

Knowledge Gaps

The TRPA currently has indicators for four types of scenic resources: (1) travel route rating, (2) scenic quality rating, (3) public recreation areas and bike trails, and (4) community design. These indicators have numerical scores representing the visual appeal of each spatial unit. Each indicator has a regulatory threshold that the TRPA tries to maintain, and measurements are taken every 5 years. None of these indicators have achieved attainment of threshold values during any of the four previous evaluations (TRPA 2006a). In addition, the USFS conducts scenic class inventories on their lands. A recent document prepared by the USFS as part of preparing its next forest plan addresses changes since the 1988 plan in the scenic conditions as measured by the 1997 Scenery Management System (SMS). It notes that there has been no recent monitoring of existing visual conditions, which means that there are no data sufficient for trend analysis on USFS lands. It calls for more monitoring, a reorganization of TRPA's Scenic Resources threshold system, and an upgraded SMS for scenic inventories (USDA Forest Service 2006b).

In terms of the built environment, there has been a trend toward larger residential structures, which are more visible around the basin and block views of and from the lake. The Place-Based Planning and Forum portions of the Pathway planning process and workshops with the Tahoe Chambers of Commerce all revealed a perception of "urban blight" in portions of the basin, where insufficient investments have been made in redevelopment of commercial properties, rental residential properties, tourist accommodations, public spaces, and infrastructure (Regional Planning Partners 2006). As a result of the Pathway planning process, the TRPA Scenic Resources staff has recently proposed new scenic quality indicators to their governing board. These indicators explicitly recognize issues like community design and the built environment, the importance of improving the scenic quality and integrity rating systems, and even light pollution.

Research Needs

Fifteen areas for potential research were identified for the scenic resource subtheme (see tabulation on page 309). These are discussed in terms of all four categories of research; data collection and consolidation, monitoring for management need, public agency management and collaboration, and program evaluation and policy design. Basic data collection and consolidation needs are focused on determining a better estimate of the public demand for improved visual resource management (S1–S6). Of interest to management agencies is the public perception of the scenic values and appearance of environmental qualities like a healthy forest, lake, or ecosystem (S2). The public's perception of a healthy forest, or the visual impact of fuels management, do not match that of a professional forester, and this can lead to conflict between staff on the ground and the general public. Issues of light pollution in the Tahoe basin were widely discussed at the science symposium, and it was recommended to develop a sense of how big an issue it actually is, how the public perceives it, and how it might be addressed (S1). The USFS document for updating the forest plan noted a similar demand by residents and visitors for night sky viewing and reductions in light pollution.

There is a broad perception (supported by TRPA Scenic Resource ratings) of increased private investment in larger single-family homes that block views and dominate viewscapes, and a decline in the visual appeal of commercial areas and rental communities owing to low investment in public and commercial areas. Some research into the accuracy of these perceptions is recommended (S3), as would be work on possible regulatory and economic incentives to address them. The draft Pathway report (TRPA 2006d) describes some details of desired future conditions and indicators for scenic qualities, in relatively vague language. The TRPA and other management agencies recommended obtaining more complete public input as a way of refining these goals and there has been increased discussion of more frequent and thorough scenic inventories (S5). One suggested way to do that is through a broader and more detailed public perceptions study or survey (S1, S2, and S3). This would provide systematic knowledge of how people want their communities to look (S6). This can be weighed against the various environmental regulations and other regulations to make policy. To date, limits to land coverage on a developing parcel have been guided almost entirely by ideas about soil capability. However, it is possible that alternatives to soil-based limitations would be useful. A "scenic quality carrying capacity" was proposed as a limiting factor to developments of all types, but particularly directed toward larger single-family residences (S6).

Monitoring for specific management needs was primarily directed toward understanding the link between questions about reinvestment and improving the built environment (S7) and studies of the public value of increased scenic resource protection (S8). Most stakeholders agree that the high scenic beauty of the Lake Tahoe region is a large part of why people live, visit, and recreate in the area, yet the actual value of scenic resources, and the degree to which public spending should be dedicated to preserving and improving them is largely unknown. A study of the value of scenic resources, both in economic and noneconomic terms (S8) was suggested. A combination of contingent valuation, hedonic valuation methods, and travel-cost studies could be conducted to provide some information on these values.

The only question regarding interagency collaboration was that of integrating the TRPA's visual resource management tools and indicators with those of the

USFS (S9). Although the different management mandates of the two agencies may not allow a single system, increased examination of the correspondence of the two systems and coordination with other public and private entities interested in scenic resource management are recommended.

As with the other subthemes, there are numerous questions related to program evaluation and policy design (S10–S15). A simple request in the community workshops was the question of whether it was feasible to put power lines underground as part of the same construction processes that will be undertaken to put in storm drainage systems and sewers as a means of improving scenic quality (S10). Overall, there were broad discussions on examining the means of directing public and private investment to those communities with the greatest visual resource declines (S14). Various participants expressed concern about homogenous residential development being a threat to "local community character." The assertion was that TRPA restrictions on coverage and other regulations have resulted in a more uniform home style: with new homes designed to maximize profit while meeting all the regulations and the outcome leading to the decline in unique visual composition of communities around the lake. Requests were made to understand the extent to which this is true, and, if it is, what might be done to induce more diverse designs (S12). Research was requested on possible regulatory and economic incentives to address various scenic resource issues involving both public and private development (S13); this included possible methods for mitigating the decline of viewscapes owing to private residential development (S15). One issue raised was examining the feasibility of a scenic easement system—analogous to conservation easements—and purchase of scenic development rights or a scenic rights trading system were also recommended as ways to balance the public demand for high-quality scenery with private property rights (S11). Visual resources were not examined in the stakeholder survey.

Noise

The noise subtheme provoked substantially less input than the other social sciences subthemes. However, some research needs were identified. Noise is an issue in the basin largely for human aesthetic reasons, although some instances of noise pollution also may affect wildlife and the quality of their habitats. For example, the northern goshawk (*Accipiter gentilis*), requires quiet and undisturbed nesting sites for breeding and is discussed as a management issue in the ecology and biodiversity chapter. Noise in the Tahoe basin is primarily anthropogenic and includes private vehicle traffic, boats, airplanes, construction, snowmaking, off-highway vehicles, and certain special events.

Knowledge Gaps

The TRPA uses a metric called the Community Noise Equivalent Level (CNEL) to assign and evaluate noise levels based on land use compatibility. The CNEL is a weighted average of all noise in a place within a 24-hour period. The CNEL standards are assigned based on land use categories and transportation corridors. A few examples of existing CNEL standards based on land use are (1) 65 decibel average (dBA) for industrial areas, (2) 60 dBA for hotel and commercial areas, and (3) 55 dBA for high-density residential and urban outdoor recreation areas. The airport CNEL value of 60 dBA applies to approved flight paths. However, TRPA Noise Resource Area staff recently presented a set of modified noise indicators to the TRPA governing board. In addition to somewhat modified decibel levels for CNEL, the proposed indicators include effects on wildlife and single-event noise levels such as low-flying aircraft.

Noise levels are monitored in only a few locations once every 5 years. This creates a temporally and spatially incomplete data set, making it hard to assess trends, adjust for temporary noise sources like construction, capture site-specific noise sources, or test actual traffic noise against the levels predicted by current noise models. In contrast, the Tahoe airport maintains a monitoring system and reports exceedances and complaints monthly (Brown-Buntin Associates, Inc. 2004).

Research Needs

Five areas of research were identified for the noise subtheme, falling into two categories of research: data collection and consolidation, and program evaluation and policy design (see tabulation on page 309). The single largest issue with regard to noise appears to be the need for a monitoring system capable of providing a more spatially and temporally complete and uniform coverage (N1). The current CNEL-driven system does not capture one-time violations and does not provide a good estimate of average noise levels. The proposed single-event and wildlife-related TRPA noise indicators also would need more thorough and effective monitoring systems. A study into the feasibility of remote sensors to monitor noise levels over extended periods could be useful. There also is an issue of the difference between the actual noise levels and the perceived noise levels of private vehicles, off-highway recreation vehicles (like snowmobiles), and other motorized transportation and recreation vehicles. Technological improvements may have reduced the actual noise production of these vehicles, but people may have over the same time become more sensitive and perceive them as incompatible with the Tahoe experience. A number of agency personnel expressed an interest in understanding the real public demand for increased noise regulations (E2).

In terms of policy evaluations, interest was expressed in examining subsidies or other public investment in noise abatement technologies that can reduce noise levels from vehicles while still allowing their current levels of use (N3). Feasibility and effectiveness studies of mitigation opportunities were mentioned as potential topics for study (N4). Studies of enforcement options could be helpful in addressing noise issues and finding resolutions to conflicts about them (N5). Noise was not explicitly addressed in the stakeholder survey.

Metathemes and Emerging Areas of Interest

There were a number of overarching research needs that cut across many of the social science subthemes and even other thematic areas in the natural sciences. Where there were very clear subtheme research questions, they are included in the sections above; however, some issues were raised frequently enough that they warrant separate discussion. This section presents information and research needs for five metathemes: (1) collaborative information management; (2) Tahoe basin community management; (3) program evaluation, policy design, and policy process evaluation; (4) fire and natural hazards; and (5) climate change impacts.

Collaborative Information Management

A conclusion of this research process was the recognition that many types of data and research results would be useful for a variety of different regulatory and management agencies, advocacy groups, private businesses, and community interests. There was a broad consensus that it would be beneficial to the entire Tahoe basin community if there were increased collaboration on funding, collection, dissemination, and storage of social science data, rather than piecemeal data collection for specific organizational needs. There has already been substantial effort made toward the archiving and storage of social science data through the establishment of the Tahoe Integrated Information Management System (TIIMS). The TIIMS was recently established as a data clearinghouse and information hub for Lake Tahoe related data. However, based on the results of the 2008 Social Science Data Needs Assessment for the Lake Tahoe basin (Kauneckis and Copeland 2008), TIIMS appears to be underused as a data clearinghouse (fig. 7.7).

The underuse of TIIMS is likely due to its relatively recent implementation and current redevelopment of its user interface; it is possible that TIIMS will become an important component of the information infrastructure for Tahoe if sustained funding is established. At least some members of the business community have expressed a willingness to join with natural resource management agencies in sharing the cost of gathering, maintaining, and distributing mutually beneficial

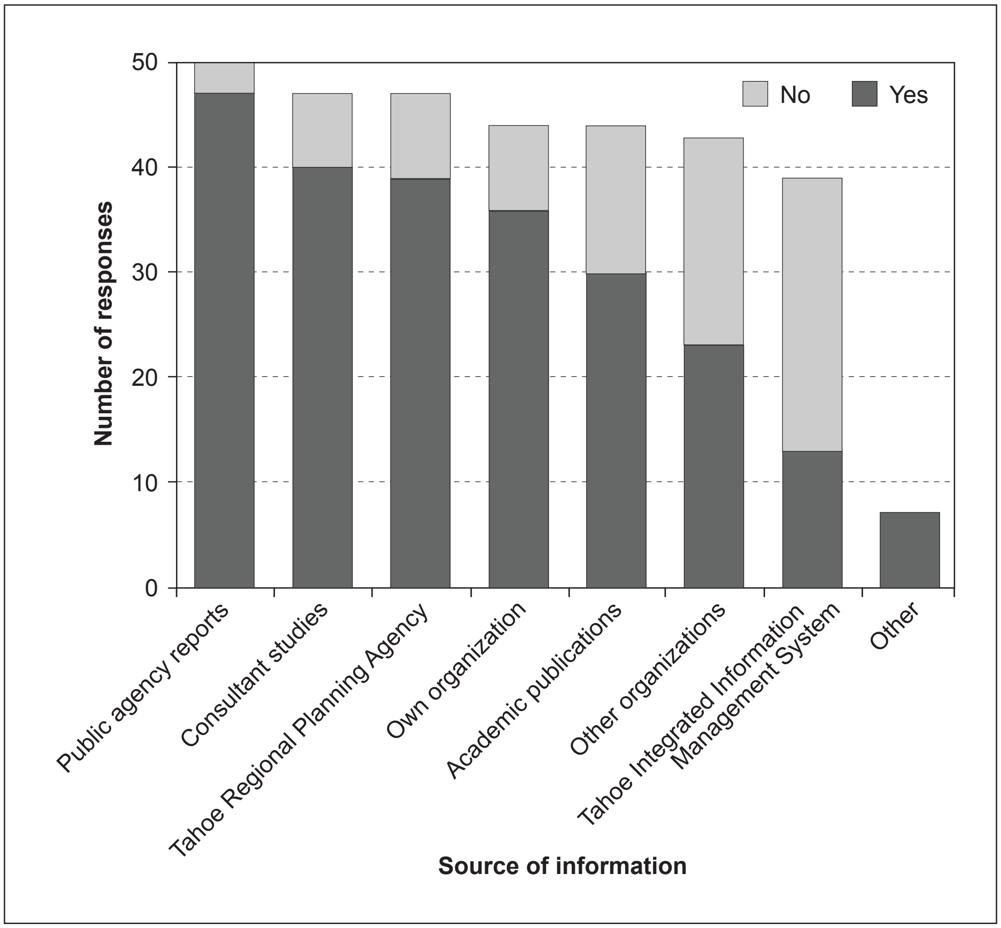

Figure 7.7—Current source of social science information (n= 50). (Source: Kauneckis and Copeland 2008).

scientific information at regular intervals. Numerous regulatory and management agencies and local governments have similarly expressed the potential utility of a clearinghouse where data could be held and distributed for common use. The Tahoe Chambers of Commerce in conjunction with the U.S. Army Corp of Engineers have recently formed a working group of stakeholders to scope the potential for developing a set of community sustainability indicators for the Tahoe basin (see U.S. Army Corps of Engineers 2008). Given the very high level of communication and collaboration already occurring among stakeholders in the basin (Kauneckis and Imperial 2007), focusing this attention on the collection and dissemination of social science information is the next logical step. Although there are challenges to designing a data product useable by such a diverse array of stakeholders, this is a broad-based interest worth pursuing.

Increasing access to the broad array of information on specific management issues adopted in other alpine-tourist-based economies was also a common point of discussion throughout the science workshop. For example, there was strong interest in the development of a "library" of consumer choice on transportation, vehicle use, and alternative modes (T17). In another example, managers were interested in better understanding how other areas have dealt with recreational conflicts (R12) and with affordable housing in resort communities (E19). Fundamentally, decision-makers feel that they may be "reinventing the wheel" in dealing with many of the challenges at Lake Tahoe and that access to information on policy options created in other areas would facilitate the policymaking process.

Creating such a useable knowledge base is a substantial challenge. However, there are a number of immediate options available. The most common means of learning what has been done elsewhere is through informal professional networks and formal professional associations and publications. This assumes continued engagement with other practitioners and would reallocate attention that otherwise goes toward more immediate tasks. An alternative to Tahoe-based managers going outside the basin is to bring in outside experts and use consultant services to summarize current understanding of a specific topic area. This is a common occurrence at Tahoe and when combined with a focused workshop with resource management agencies can be a very effective means of getting immediate questions answered. However, there are disadvantages to this method of knowledge diffusion. Typically, the input by one person is less useful and reliable than a broader array of opinions. Given the already high level of collaboration at Lake Tahoe, scheduling by top managers tends to be overallocated and unless immediately relevant, attendance to events is often low. Additionally, most managers prefer information available on their own schedule, thus the preferred source of social science information is standard compilations in existing reports (fig. 7.7).

With the advent of Web-based knowledge systems, there are a number of technical options that may be worth exploring. The TIIMS represents an important first step in collecting Tahoe-related research by developing and cataloging reports and data in a searchable format. However, there have been complaints about difficulties in accessing data stored on TIIMS. Information consumers are increasingly demanding immediate usability of the information output and TIIMS structure as a data clearinghouse does have some limitations. Given the specificity of the knowledge needs for particular policy issues, and the underlying complexity of many of the questions public and private stakeholders are interested in addressing, there are no immediate simple technical fixes. Web-based delivery of information would require substantial upfront investment in an information infrastructure and continued resources dedicated to upkeep and management. There are, however, some potential technology-based experiments that could be considered. One of the most-used sources of Web-based information is open-source discussion groups dedicated to specific topics. If Tahoe-based decisionmakers are having problems finding information on the impact of something like parking fees on recreational experience, it is likely that other transportation and recreation managers have as well. Lake Tahoe is often on the forefront of emerging management issues and this could potentially be leveraged to develop new discussion groups with resource managers facing similar issues. It is recommended that this be done experimentally and in close association and perhaps co-sponsorship with professional associations. This might involve only a subset of alpine lake resource management associations, or even just agency officials within the basin. The challenge is to design a means of leveraging the experience and knowledge of other alpine-resort-based communities. Other options include various forms of information and knowledge architectures. For example, an open discussion and contribution-based Web site such as a "Tahoe-wiki' where general questions could be posted with response options open to other resource managers or the general public. Many Tahoe residents do tend to be highly educated and can bring time and technical expertise to management questions. There are obviously numerous challenges with designing digital knowledge systems that produce useful results; however, Tahoe's unique environmental characteristics, national prominence, and proximity to the epicenter of the digital economy may give it an advantage in being at the forefront of the development of new knowledge systems for managing natural and human-made environments.

Tahoe Basin Community Management

A consistent point of discussion was moving management questions from a central focus on environmental management toward broader issues of basinwide community management (TRPA 2007a, b). This was not directed at weakening environmental regulations, as most stakeholders have come to accept the importance of environmental quality as central to the character of Lake Tahoe, but rather an attempt to bring a similar commitment to social aspects as well. This represents the natural evolution of public management questions in the Tahoe basin as businesses and communities have adapted to the regulatory structure necessary to preserve lake water quality and the broader ecosystem, they increasingly understand the interdependence of the Tahoe basin in terms of a regional economy and a set of interconnected communities.

Examples of immediate areas of research integrated with community decisions included basinwide methods for prioritizing and improving local infrastructure that impact local quality of life. Although the allocation of infrastructure projects is partially discussed in the EIP plan, some stakeholders felt the central focus on environmental aspects may weaken some community priorities. A related infrastructure issue was that of the lack of DSL or other high-speed Internet access basinwide. This may be an important business diversity issue for likely a large percentage of Tahoe-based professionals who work out of home offices. Discussions of the lack of a basin- or regionwide communication infrastructure that would help emergency response in the aftermath of a natural disaster, extreme weather event, or other emergency situation were an additional concern. Coordination of the various local government units could improve the response, but there is little direction or infrastructure to support it. It is recommended that alternative energy and environmentally sustainable design be considered part of the ongoing Tahoe basin management, and yet they do not fit into any thematic category. There has been some local interest in the development of regional forest biomass conversion facilities for renewable energy. Additionally, participants in workshops held by the chambers of commerce expressed the need to further develop public gathering places, community and nonoutdoor recreation centers, increase the level of arts and culture, town centers, and other community-related amenities. Information on the return to public investment as well as how to better target the type of public space infrastructure investments was a shared concern by both local planners and regulatory agencies, and private businesses.

A number of recent activities suggest there is a substantial movement toward redirecting and coordinating management decisions at the community level. The Pathway process involved a number of direct engagements between the regulatory agencies and communities. The Community Enhancement Program produced a set of community visions (from which many of the questions examined in the survey and discussed in this chapter were drawn). The recent effort toward the development of a set of sustainability indicators (U.S. Army Corps of Engineers 2008) suggests substantial room for collaborative work between the public and private sectors.

The discussion above presents the primary issues brought forth during meetings and workshops, yet additional insight is revealed in the stakeholder survey results. Based on a review of the literature and discussion with local stakeholders, the survey was designed to specifically capture other community-based research issues not directly addressed in the subthemes above. Community well-being consistently ranked high among issues addressed in the survey (fig. 7.4). In terms of specific community well-being issues, school quality ranked as most import, followed by fire vulnerability, the population living below the poverty line, housing affordability, and public space (fig. 7.8).

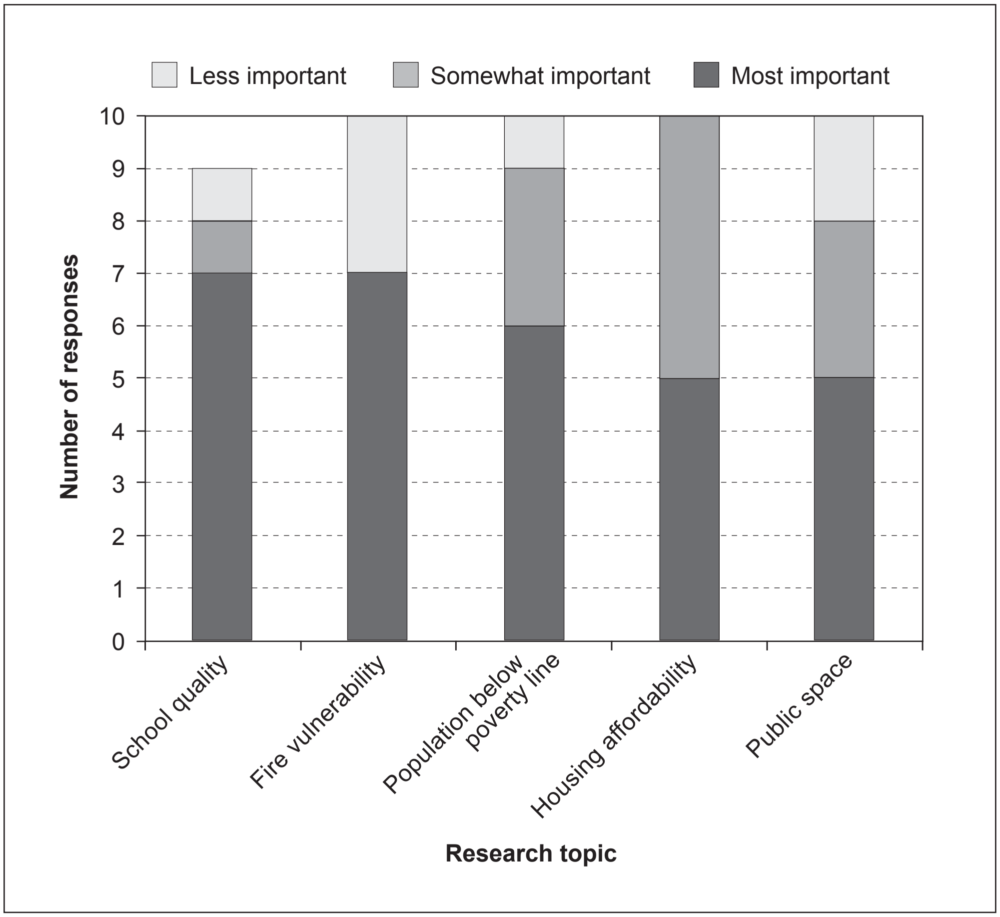

Figure 7.8—Ranked importance of community well-being issues (n = 10). (Source: Kauneckis and Copeland 2008).

An examination of the type of data needed for each of the above (table 7.5) reveals that the most important need is for information on current status, followed by future projections and general trends. The spatial extent of the data varies according to the specific issue (table 7.5). School quality data were both important at the basin and local political jurisdiction level. Fire vulnerability was included in the survey under community management, and interestingly the spatial extent of the necessary data was at the individual level, likely a recognition of the importance of establishing defensible space on private parcels. Fire risk was also considered important at all other spatial extents. In terms of the temporal extent of data, the results were predictable, with school quality and the population below the poverty line important annually, fire vulnerability and public space seasonally, and housing affordability biannually and seasonally, probably recognizing the unique nature of the seasonal employment flows to Tahoe.

Table 7.5—Community management

	Community	School quality	Fire vulnerability	Population below poverty line	Housing affordability	Public space
				Number of responses		
Type	Current status	5	**6**	**6**	**6**	4
	Future projections	2	5	**6**	5	4
	General trends	3	3	2	**4**	3
Spatial	Local political jurisdiction	**5**	4	**5**	**5**	3
	Community level	3	**4**	**4**	2	3
	Tahoe basin	**4**	3	3	2	3
Temporal	Seasonally	1	**4**	2	2	3
	Annually	2	1	**3**	1	1
	Biannually	1	0	0	**2**	0

Note: Items in bold represent the most frequent responses in each row.

Program Evaluation, Policy Design, and Policy Process Evaluation

Many participants in the various workshops and meetings, from the public, private, and nonprofit sector expressed interest in a variety of public policy evaluation issues. These are grouped here into three overlapping areas of policy research: (1) program evaluation, (2) policy design, and (3) policy process evaluation. Program evaluation involves research questions on the efficacy, efficiency, and equity of current public programs and regulatory policies implemented in the basin. Policy design addresses questions of the specific components of existing and new programs and how these can be adjusted to improve desired outcomes. Policy process evaluation includes research and methods for improving the decisionmaking and collaborative process itself. Typically this includes such issues as coordinating policy implementation across different agencies, public management, managing program implementation in networked environments, developing conflict resolution mechanisms, and increasing public participation.

In terms of program evaluation needs, a number of participants, including management agencies and representatives of the Tahoe Chambers of Commerce, expressed interest in identifying conflicts between various regulatory policies. One example discussed was installation of a flashing light to warn motorists of a crosswalk, which was proposed and planned but could not be implemented owing to its direct violation of TRPA scenic regulations. Another is the perceived incompatibility of vegetation management for fuel reduction and habitat enhancement versus the impacts these actions can have on soil and water quality. These interventions produce positive public outcomes, but they present challenges for reconciling local and regional goals and clearly communicating actions to the public. Developing an explicit means for the systematic investigation of these types of clashes was also discussed. The fact that the request was not to resolve specific conflicts, but rather for a process to frame future discussions, suggest various methods of policy process evaluation could be useful. This incompatibility is further discussed in the recent emergency fire management report (California-Nevada Tahoe Basin Fire Commission 2008).

The social science data needs survey was designed explicitly to address various aspects of the policy environment at Lake Tahoe and included questions about a variety of public agency management issues (fig. 7.9). The highest ranked items of interest were the relationship between government agencies and the public, followed by improving interagency cooperation, evaluation of the effectiveness of current policies, cost-effectiveness, and conflict reduction tools.

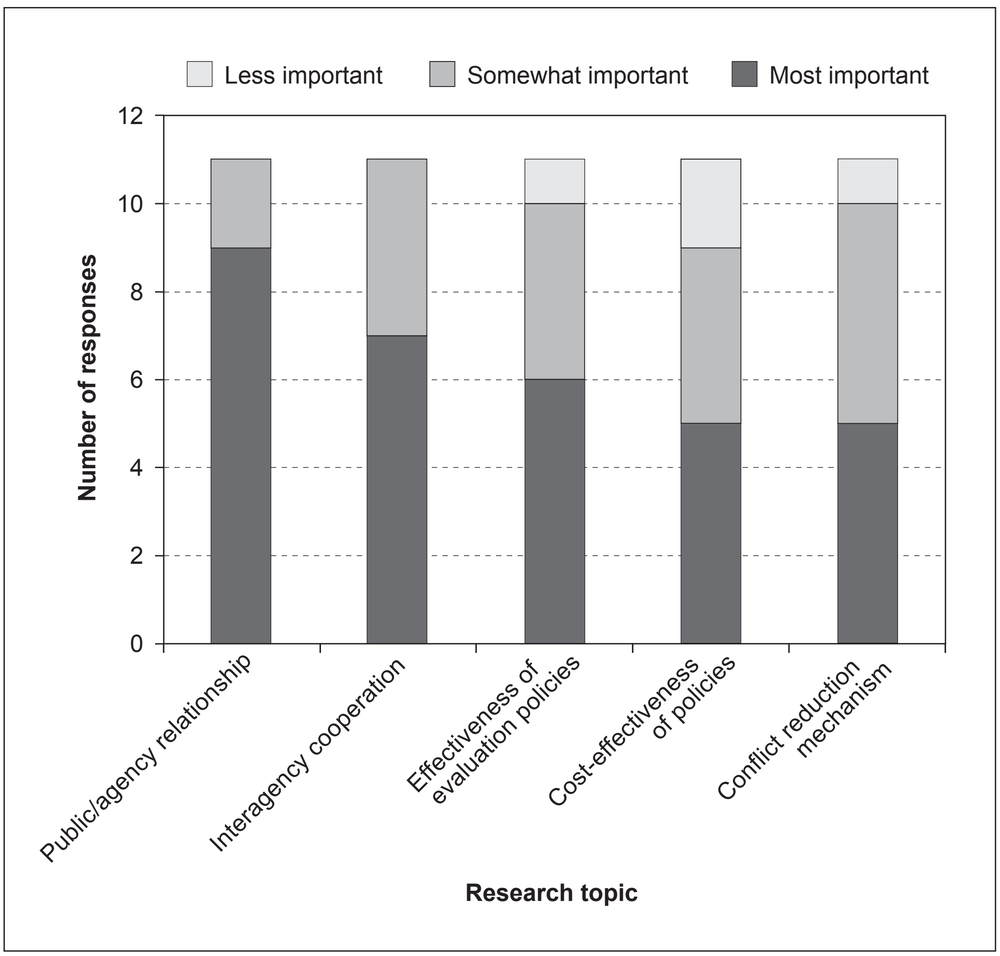

Figure 7.9—Ranked importance of public agency management issues (n = 11). (Source: Kauneckis and Copeland 2008).

With regard to the types of data, current status was highest in importance in the areas of public/government relations, interagency cooperation, and conflict reduction (table 7.6). Evaluation of program effectiveness was directed toward future projections suggesting an emphasis on improving the participation and compliance with existing policy programs. Across all issue areas, the spatial extent of interest was the Tahoe basin, with some attention to administrative jurisdiction for effectiveness evaluation of policy and cost-effectiveness. The temporal extent was generally focused on annual or biannual evaluations (table 7.6).

Table 7.6—Public agency management and collaboration

	Agency	Public/ agency relationship	Interagency cooperation	Effectiveness of evaluation policies	Cost effectiveness of policies	Conflict reduction mechanisms
				Number of responses		
Type	Current status	**5**	4	1	2	4
	General trends	2	2	2	**6**	2
	Efficiency improvements	1	1	2	**3**	**3**
Spatial	Local political jurisdiction	2	1	0	0	**3**
	Administrative jurisdiction	0	1	3	**4**	2
	Tahoe basin	**8**	7	5	5	6
Temporal	Monthly	2	2	1	1	**3**
	Annually	3	2	**4**	3	1
	Biannually	1	0	1	1	**3**

Note: Items in bold represent the most frequent responses.

A related issue discussed by some public agency representatives was the extent to which the public understood the environmental quality issues at Lake Tahoe and the impact of the various policies. Although some research has been conducted on public attitudes and perceptions of the TRPA and its regulatory policies (Kauneckis 2008, TRPA 2005a, Weible 2007), very little work has been done pertaining to the role of public education in helping organizations and agencies in the basin promote collaboratively defined desired conditions (for an exception see Ward et al. 2003). This includes understanding the impact of current public information and interpretive programs, as well as how these can be designed to be more effective.

One of the best examples of the crosscutting nature of policy evaluation is the current program of private and commercial property BMPs. In the Lake Tahoe basin, BMPs are structural and landscape design components intended to reduce soil erosion and polluted runoff from private parcels. Best management practices include building infiltration systems for stormwater runoff from impervious surfaces such as driveway and rooftops, mulching and revegetating bare or disturbed soils, stabilizing steep slopes and loose soils, and paving dirt driveways and roads. Best Management Practices were required on new construction and remodeling projects beginning in the 1980s. The TRPA instituted BMP requirements as part of its basinwide ordinances in 1992 and in 2002 created the BMP Retrofit Program targeting existing structures as well as new constructions. As of 2003, TRPA ordinance requires BMPs on all private residential, commercial, and industrial parcels. Implementation of BMPs on existing private parcels was prioritized into three watershed groups, and deadlines have been set for compliance and certification. The deadlines for compliance in priority 1 and 2 areas passed in 2000 and 2006, respectively, and are set for 2008 for priority 3 areas. Despite active public outreach via TRPA, university cooperative extension programs, resource conservation districts, and the Natural Resources Conservation Service, average rates of compliance for the BMP retrofit program are at 16 percent for California and 25 percent for the basin as a whole (TRPA 2009: 25). So far there has been little attempt at enforcing BMP retrofit requirements on existing structures and few actual sanctions imposed. Compliance has occurred on a voluntary basis and is likely linked to home renovations (Kauneckis 2008).

The environmental aspect of BMPs is the primary management strategy for dealing with water quality and soil management issues in the Tahoe basin. Their environmental aspects are discussed in the "Water Quality" and "Soil Conservation" chapters. Although relatively limited, some work has evaluated the water quality benefits of private and commercial BMPs (see Schuster and Grismer 2004). However, BMPs also are important to understand as a component of the social sciences, as the primary questions raised by stakeholders involved increasing implementation on private parcels, the efficiency and cost-effectiveness of current designs and location selection, and means of coordination and prioritizing public investment in community-scale BMPs for targeting the most effective projects.

The most salient contemporary program design issue is that of modifying regulations that work at cross purposes for protecting environmental quality and reducing excess forest fuels following the Angora Fire (California-Nevada Tahoe Basin Fire Commission 2008). This included clarifying the private homeowner's responsibility to clear vegetation and pine needle debris to create defensible space and requirements to maintain native vegetation and ground cover to minimize erosion and polluted runoff. This issue also extends into undeveloped areas such as fuel management of areas in stream environment zones, and balancing forest thinning practices and biomass management with water quality and erosion control functions.

Social science applications for improving environmental management include aspects of the management organizations as well as those of the public. Issues of engaging public participation, compliance, information, education, and general relationships between public agencies and private citizens also were addressed explicitly in the stakeholder survey. Public willingness to participate in programs was ranked as the most important, followed by public understanding of environmental issues at Lake Tahoe, public perceptions and understanding the effectiveness of current policies, access to information on BMPs, and general knowledge of public policies (fig. 7.10). In terms of the types of information needed, the majority of social science research needs were around items of current status, with some attention to future projects (participation and perceptions of policy effectiveness), and efficiency improvements (table 7.7). The spatial extent of the data requirements were almost universally at the basin level, with some interest in community level.

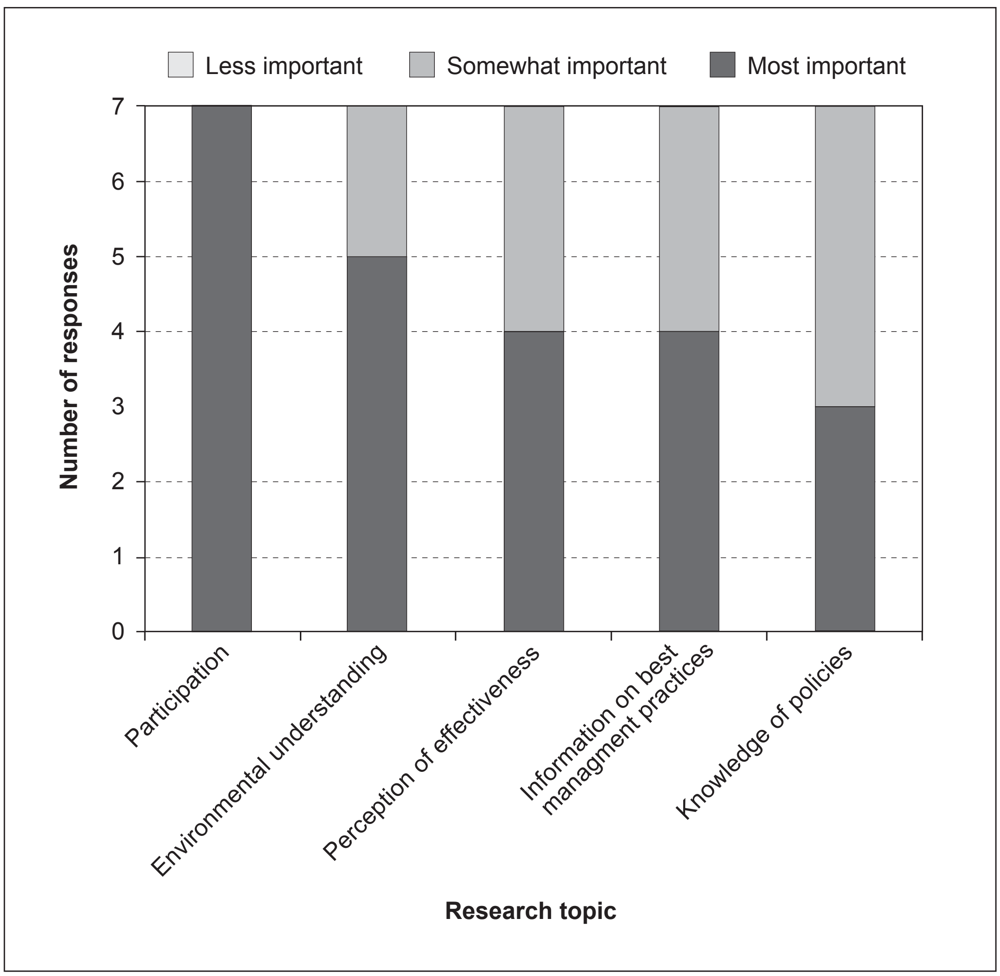

Figure 7.10—Ranked importance of public information issues (n = 7). (Source: Kauneckis and Copeland 2008).

Table 7.7—Public information and outreach

	Public	Participation	Environmental understanding	Perception of effectiveness	Information on Best Management Practices	Knowledge of policies
				Number of responses		
Type	Current status	3	2	3	3	**6**
	Future predictions	**3**	1	**3**	2	2
	Efficiency improvements	**2**	0	**2**	**2**	**2**
Spatial	Community level	2	0	0	1	**3**
	Administrative jurisdiction	0	1	1	1	**2**
	Tahoe basin	4	3	**5**	3	4
Temporal	Seasonally	**3**	2	**3**	0	2
	Annually	0	0	0	**3**	1
	Every 5 years	**2**	1	**2**	**2**	1

Note: Items in bold represent the most frequent responses in each row.

Although the expected relationship was that this information would be most useful on an annual basis, respondents indicated that seasonal was more important. This is tied to the winter/summer recreational seasons and likely the need to understand the new dynamic of second-home ownership.

With much of the policy focus at Tahoe on issues of private land management, such as BMP implementation and fuels management, the role of public participation is becoming increasingly important. However, the growth of second-home ownership presents challenges to maintaining public involvement in community and basinwide issues. Yet there are a broad array of methods for informing and engaging the public in policy decisionmaking including traditional forms of public engagement through community workshops, consensus visioning, public education, and interpretation. There also are a number of methods for more explicitly addressing the role of the public. Community-based mapping, using Web-based geographic information systems or other visualization techniques were discussed in various meetings. The TIIMS is currently developing an online map service to show the location and relevant information about EIP projects, and progress on defensible space on a parcel-by-parcel basis. Commercial and other open-source data visualization programs also are available for better presenting information to the general public. Other technology-based methods include such approaches as alternative futures and consensus modeling. Alternative-futures modeling presents various possible scenarios in land, water, and natural resource management and permits stakeholder discussion around the state they would prefer for their community. Alternative-futures modeling has been useful in a number of environmental management applications (Baker et al. 2004, Van Sickle et al. 2004). Consensus and alternative-futures modeling involves simulations of different scenarios in order to engage both stakeholders and the broader public in terms of the consequences of their actions (or inaction). This typically presents visual output that is easily interpreted by the public and allows various parameters over which decisions can be made to examine outcomes (Costanza 1998, Van Den Belt 2004).

Although the history of the creation of the current regulatory structure at Tahoe accompanied a high degree of contention, today it may offer a competitive advantage for marketing Lake Tahoe as a center of businesses and community sustainability. There are numerous areas of potential collaboration between the public and private sectors for not only data collection that serves a common interest, but also creative partnerships that move beyond regulatory policy and toward forms of voluntary and market-based policy instruments. There has already been some success with relatively creative programs such as transferable development rights and the BMP programs (Kauneckis and Reid 2006, Reid and Kauneckis 2008). Other areas worth exploring might include formal recognition of environmentally friendly activities by Tahoe-based businesses through green business certification programs. There are a number of well-established industry-specific, regional and international environmental management and certification systems (ISO 14001 and Europe's Green Dot are the best known). There is good reason to consider creating something like a "Tahoe Blue Dot" system that can simultaneously engage and reward the business community and allow the marketing of regulatory compliance as an asset and sustainable business practices. Other nonregulatory approaches can include various forms of "social marketing." Social marketing programs represent a method of communicating public goals, targeting programs to citizens, and focusing the distribution of information to specific population subsectors. Rather than regulatory policy and negative sanctions serving as the principal tools to increase participation in public programs, it relies on information and positive psychological rewards using methods from the private sector to gain brand loyalty and understand market niches. Successful applications of social marketing toward public goals have been noted in public health and human services delivery (Goldberg et al. 1997, McKenzie-Mohr and Smith 1999).

Managing Fire and Natural Hazards

The effects of wildfire and fuels management were crosscutting themes in many of the discussions. Following the 2007 Angora Fire, fuels management became particularly salient to the public and government agencies. Additionally, the presence of faultlines in the basin has also alerted stakeholders to the possible threat of seismic events. Both hazards generate important social science needs as well. A major forest fire in or near the Tahoe basin would have broad effects on all of the theme areas considered in this science plan, including most of the social science subthemes. Fire impairs both the quality and quantity of recreation and scenic resources, and a major fire could do so for an extended period. This would have broad implications for the regional economy, both in terms of direct and indirect costs. The more immediate economic concerns have to do with paying for fuels management on public, private, and state lands, and prioritizing fuel reduction projects. Other concerns discussed in stakeholder meetings include the social acceptance of various treatment options for forest fuels.

Transportation issues are directly linked to community safety questions and most discussions regarding public agency management and natural disaster management were directed at creating a basinwide communications network for public officials. The Tahoe basin is a seismically active area with potential for large-scale events including earthquakes, landslides, and earthquake-triggered seiche waves in the lake that would act like a tsunami and flood major portions of the near-shore areas (Ichinose et al. 2000). Assessment of the vulnerability and resilience of transportation networks, recreation areas, and communities to these natural hazards is recommended, so that mitigation strategies can be developed and their likely effectiveness understood. This will certainly aid management agencies and local governments in long-term planning goals.

Climate Change Impacts

Finally, global climate change represents a relatively new research area that deserves some discussion. Because the projected changes are so broad-based, there are impacts on all the subthemes discussed in this chapter. The most immediate effect would be in terms of the interactions between recreation, scenic resources, and the local economy.

If changes occur as projected by most climate models, the Sierra Nevada is likely to experience substantial reductions in the amount of snowfall, and the snowpack that does exist is expected to melt off earlier in the year (Cayan et al. 2006). Both of these effects will lead to a reduced areal extent and season length for ski resorts and backcountry snow-based recreation while simultaneously increasing the season of some forest-based recreation such as hiking and mountain-biking, all of which are important parts of the recreation experience at Tahoe. Changes in precipitation and temperature will likely affect vegetation and pest dynamics and increase the threat of major forest fires (Ibañez et al. 2006, Westerling et al. 2006). The short- and long-term economic responses to, for example, a ski season shortened by the reduced snowpack expected from climate change or summer recreational opportunities impacted by increased wildfires are important to assess now so that mitigation and response plans can be developed. Reduction in snowfall, the risk of wildfire, and resulting impact on water quality and scenic resources related to forest cover all suggest major changes for the regional economy, which could be examined through alternative futures modeling.

Near-Term Social Science Research Priorities

The most consistently discussed topics related to issues of transportation, economics, recreation, and the quality of the built landscape. Common metathemes were the development of a collaborative information management infrastructure, increasing the evaluation and effectiveness of current policy, a refocusing of management decisions toward the community level, and management of fire hazards and climate change impacts. Table 7.1 illustrates items identified as the highest priority.

The selection of this subset of priorities was based on a number of criteria. First, a social science research issue area had to reappear across the multiple information collection methods used here: literature review, stakeholder meetings and workshops, focused discussions with key public and private representatives, and the stakeholder survey. Second, there was an estimation of the complexity of the research issues and the likelihood that resources dedicated to a specific topic would lead to immediate improvements in environmental management decisions. This was balanced against a movement toward more complex tasks and laying out the necessary information infrastructure for improving long-term decisionmaking as discussed in more detail below. Finally, emphasis was placed on research issues that served the broadest array of stakeholders. Those that were requested by a mix of private, public, and community interests were considered more important than those of a smaller set of agency representatives. The specific justification for the selection of priority research items are indicated in table 7.1. The conceptual model in fig. 7.5 illustrates the relationship between the highest priority social science research needs and the causal driver and linkages to specific management components.

In the opinion of the authors, the crosscutting metatheme of collaborative information management is the highest overall priority. This is based on three rationales. First, this was the most common request across all the subthemes and by that fact alone can be ranked as the highest priority. Second, in terms of practically advancing the goals of this document, strategically allocating resources toward data collection will allow a common focal point for stakeholder input by creating a platform for distribution of results from other research areas. Third, there has already been substantial activity by stakeholders in this direction. Input from the chambers of commerce has enthusiastically expressed support for joint data collection and a subset of priorities for data inventory and consolidation has recently been released (U.S. Army Corps of Engineers 2008). Taking advantage of the current level of interest and the resources that have already been dedicated should move this to the top priority. Creating a platform for a small subset of common topics of interest will make data collection and consolidation in each of the individual subthemes easier. There are exceptional opportunities for creative public-private cooperation.

There also has been interest expressed toward the creation of a Tahoe basin decision-support system. Decision-support systems (DSS) use a common computer platform that brings together multiple data sources on management issues to better inform decisionmakers about the relative tradeoffs of various policy options. These have most commonly been used for natural resource management agencies making decisions for multiple-use areas; however, there is considerable potential for using DSS for integrating the social sciences with environmental goals. The advantage of a DSS is that it creates a library of integrated data sets, models, and methods. It can act as a focal point of discussion for research across different disciplines and stakeholders. Additionally many are scalable and present data in a useable visual output that implicitly incorporates uncertainty and highlights missing and needed data (Reynolds et al. 2000). The concurrent discussions on the implementation of DSS and community indicators by very different stakeholders presents an opportunity for better integrating the social sciences with management decisions.

It is worth repeating a couple of final comments and caveats. The process outlined here for scoping the need and form of various types of social science data was intended to develop a framework for further discussion, not the priorities of data collection needs. These priorities are best determined by specific stakeholders and focused on direct policy needs. This is particularly true in collaborative situations involving multiple organizations as much of the academic literature stresses that collaboration works best when there are substantive outcomes that each participant recognizes as useful (Kauneckis and Imperial 2007, Lubell 2004, Singleton 1998, Wondolleck and Yaffee 2000). This document outlines a broad array of social science data needs and perceptions of the relative utility of various forms of data in terms of the type and spatial and temporal scales. However, it does not measure the costs of obtaining the data in its most useful form, nor the willingness by stakeholders to commit resources toward the collection, management, and distribution of useful information products.

There may be opportunities to advance the research needs discussed here by establishing closer ties with one or more of the regional campuses. The University of California, Davis and the Desert Research Institute already have close research connections with resource managers in terms of the natural sciences. A similar effort can be made in the social sciences. University of California, Davis has numerous departments—particularly the Department of Environmental Policy—that can bring expertise and student resources to many of the research issues discussed in this chapter. The University of Nevada, Reno (UNR) likewise has seen recent activity in expanding its research capacity in the social sciences. New research centers and programs established in the past 5 years include the UNR Academy for the Environment, the School of Journalism's Interactive Environmental Journalism program, in addition to well-established programs in cooperative extension and other departments. Graduate programs on both campuses include business and economics, resource economics, land use planning, public administration, and policy analysis. Much of the research discussed here involves relatively straightforward data collection, consolidation, and statistical analysis, all of which are amendable to graduate student research.

Finally, it is worth returning to the concepts discussed earlier about the distinction between the collection and consolidation of data, making that data relevant and contextualized for informing policy, and turning that information into knowledge about the social dynamic of Lake Tahoe. Although the feasibility of data collection and research on the various topics of interest listed here has not been explicitly measured, few of the issues are beyond the scope of contemporary social science research methods. However, some of these studies would require substantial costs and are best addressed in terms of the relative benefits to informing policy decisions. Although the majority of input from stakeholders was on data collection, most of the subsequent discussion was about its priority as useful information and bringing the relevant knowledge to bear on policy decisions. Because of the high costs of primary data collection and continued monitoring, it is recommended that the starting point of prioritizing research efforts be on the direct application of the information for a specific management need, rather than only a generalized unspecified perception of the importance of more information on a topic. Stakeholder meetings often included interest in having information on an issue of concern without the necessary followup discussion of how that information can be put to direct use. Focusing on the management use of prior data collection efforts will help focus the priority of even basic data collection and consolidation, as well as assist in honing it down to those pieces of information that will best inform the broadest array of decisions and serve the most stakeholders.

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