Chapter 3: Air Quality[1]

A.W. Gertler,[2] T.A. Cahill,[3] T.M. Cahill,[4] S.S. Cliff,[5] C. Emmett,[6] J. Koracin,[7] H. Kuhns,[8] J.V. Molenar,[9] J. Quashnick,[10] and J.E. Reuter[11]

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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[2] Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512.

[3] University of California, Davis, Department of Physics, Davis, CA 95616.

[4] Arizona State University, Department of Integrated Natural Sciences, Tempe, AZ 85287.

[5] University of California, Davis, Department of Applied Sciences, Davis, CA 95616.

[6] Air Quality Program, Tahoe Regional Planning Agency, Stateline, NV 89449.

[7] Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512.

[8] Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512.

[9] Air Resource Specialists, Inc., Fort Collins, CO 80525.

[10] Sierra Nevada Environmental Consulting, South Lake Tahoe, CA 96150.

[11] University of California, Davis, Department of Environmental Science and Policy, Davis, CA 95616.

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.

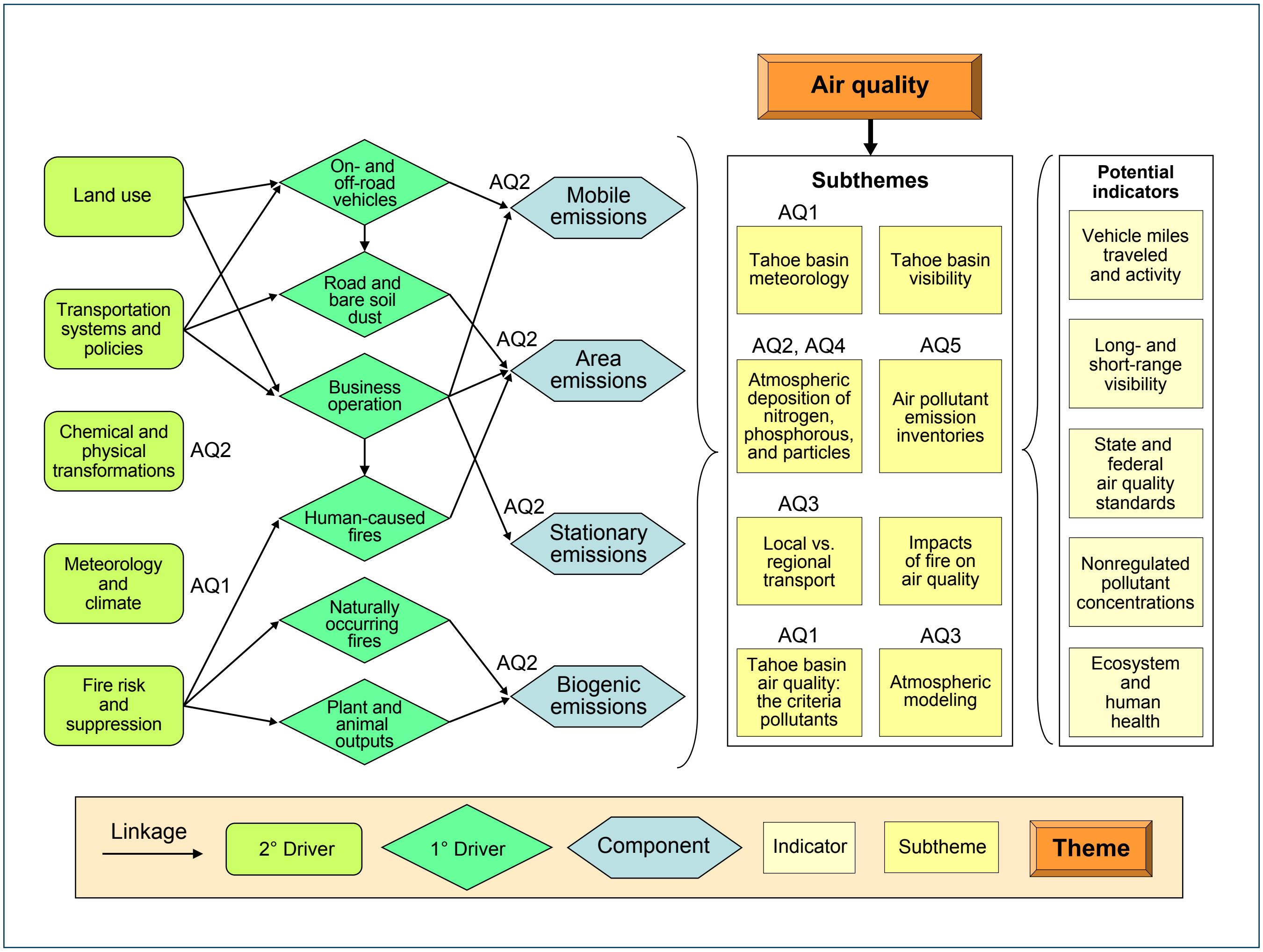

Figure 3.1—Conceptual model for Lake Tahoe basin air quality (AQ) subthemes. Identified are the primary sources of emissions in the Lake Tahoe basin airshed, the natural and human-caused drivers that affect these emissions, and arrows indicating the linkages among drivers and emission sources. These 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,

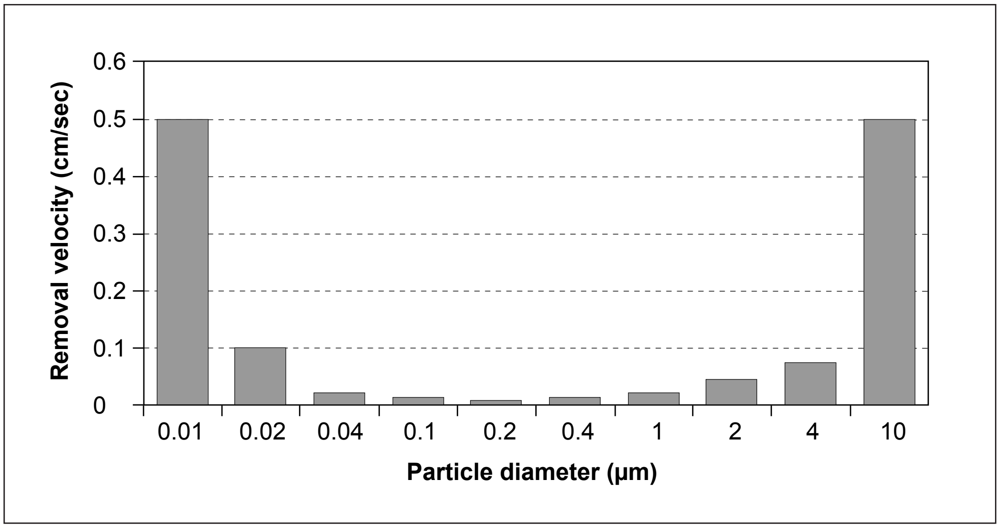

Figure 3.2—Plot of deposition velocities for particles. Above 0.3 μm, gravitational settling dominates, whereas below 0.2 μm, diffusion to surfaces dominates.

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,

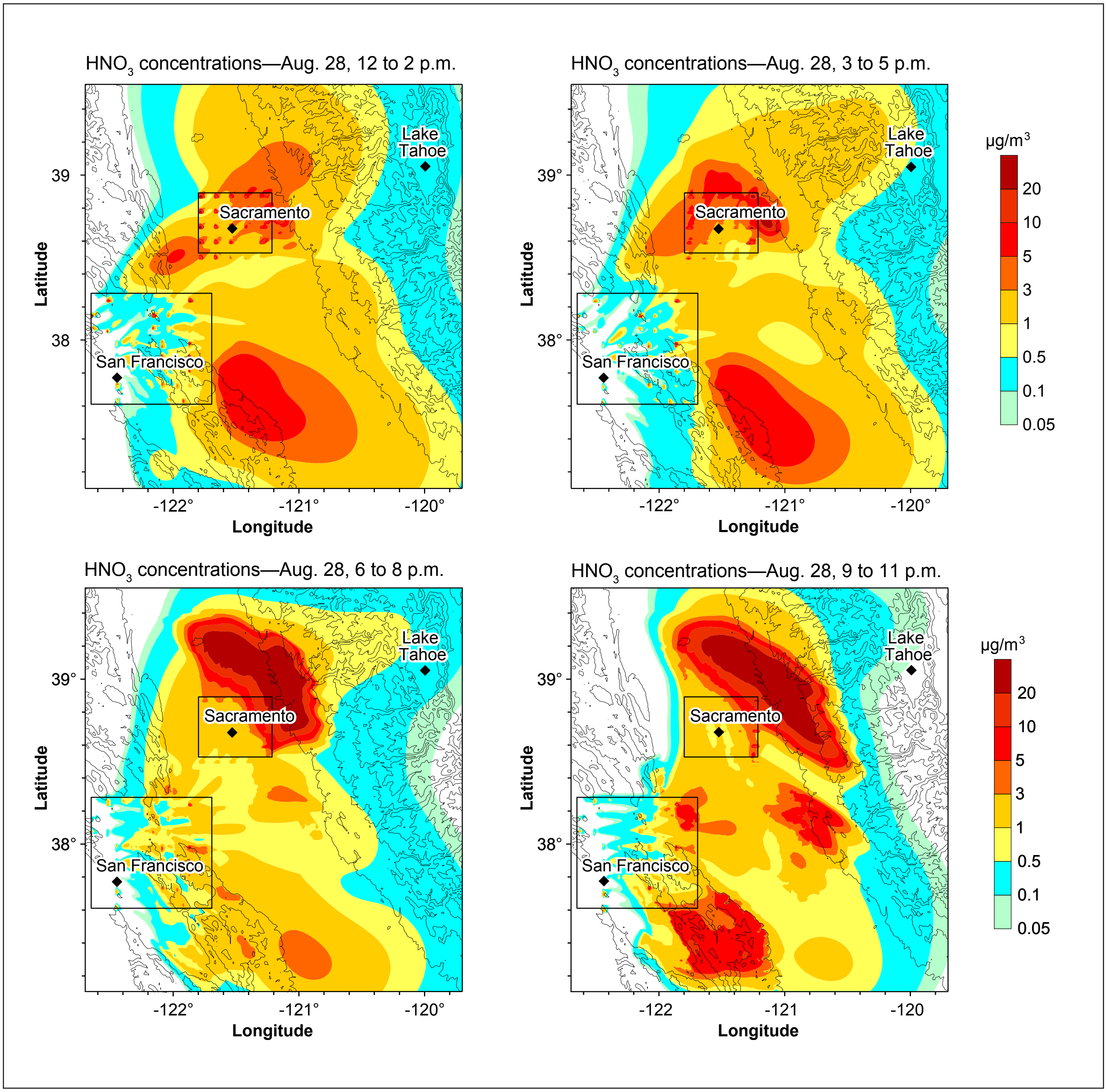

Figure 3.3—Nitric acid (HNO_3) ($\mu g/m^3$) plume evolution from the Central California Valley on August 28, 2000, beginning at noon (left panel) and continuing to 11 pm (right panel) from Gertler et al. (2006). Concentrations (filled contours overlaid with topography) are averaged over 3-hour intervals. 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.

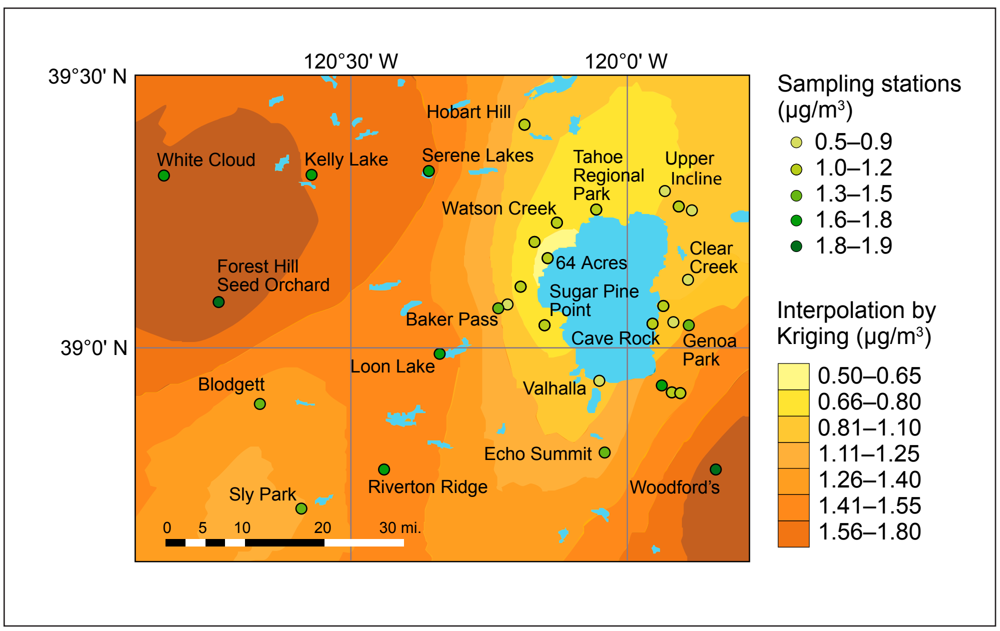

Figure 3.4—Distribution of ambient nitric acid (HNO_3) concentrations ($\mu g/m^3$) in the Lake Tahoe basin and its vicinity in the 2002 summer season from Gertler et al. (2006). Maximum levels (dark brown) are observed west of the lake and decrease with increasing elevation.

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				5-year trend
	1991	1996	2001	2006	
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 µg/m^3	150 µg/m^3
	Annual arithmetic mean	20 µg/m^3	None
Particles less than 2.5 µm in diameter	24 hr	Same as federal	35 µg/m^3
	Annual mean	12 µg/m^3	15 µg/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.

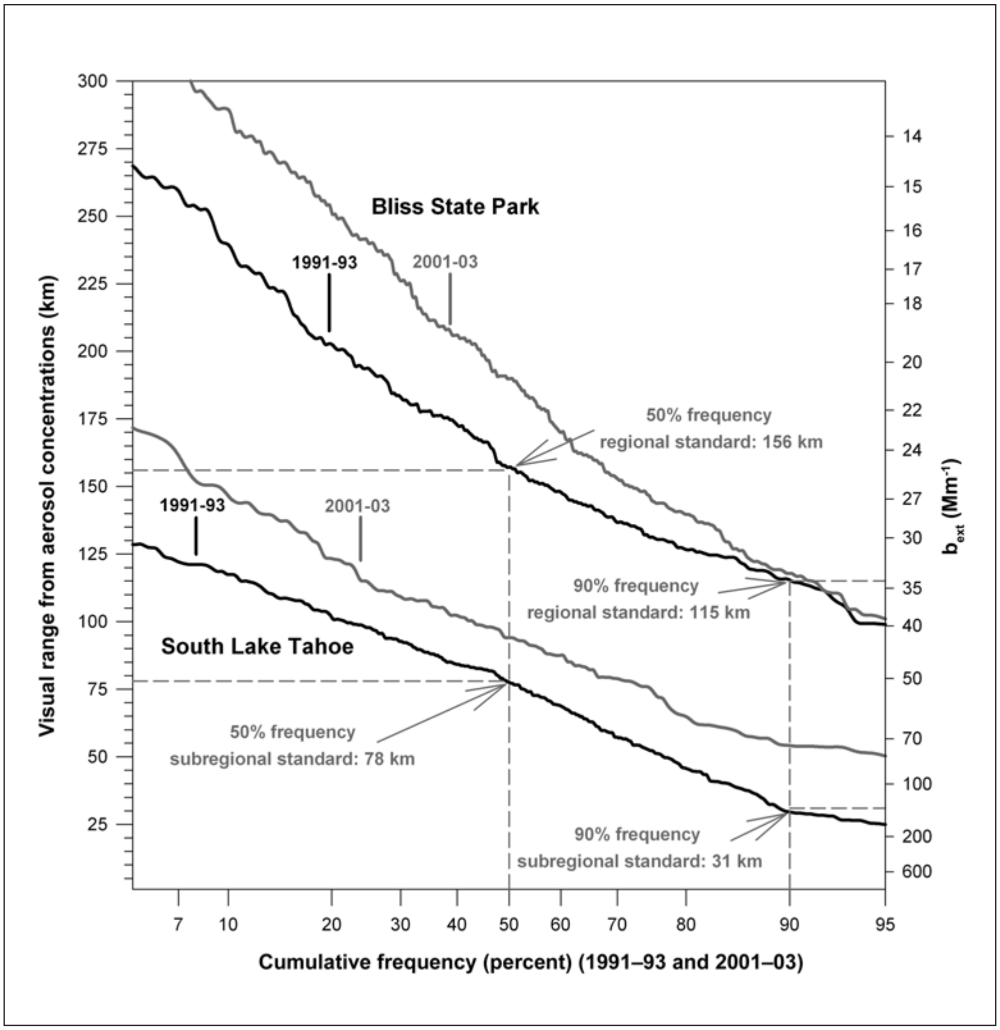

Figure 3.5—Tahoe Regional Planning Agency visibility standards: cumulative frequency plots of reconstructed extinction for 1991–93 (baseline year) and 2001–03 (from TRPA 2005).

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.

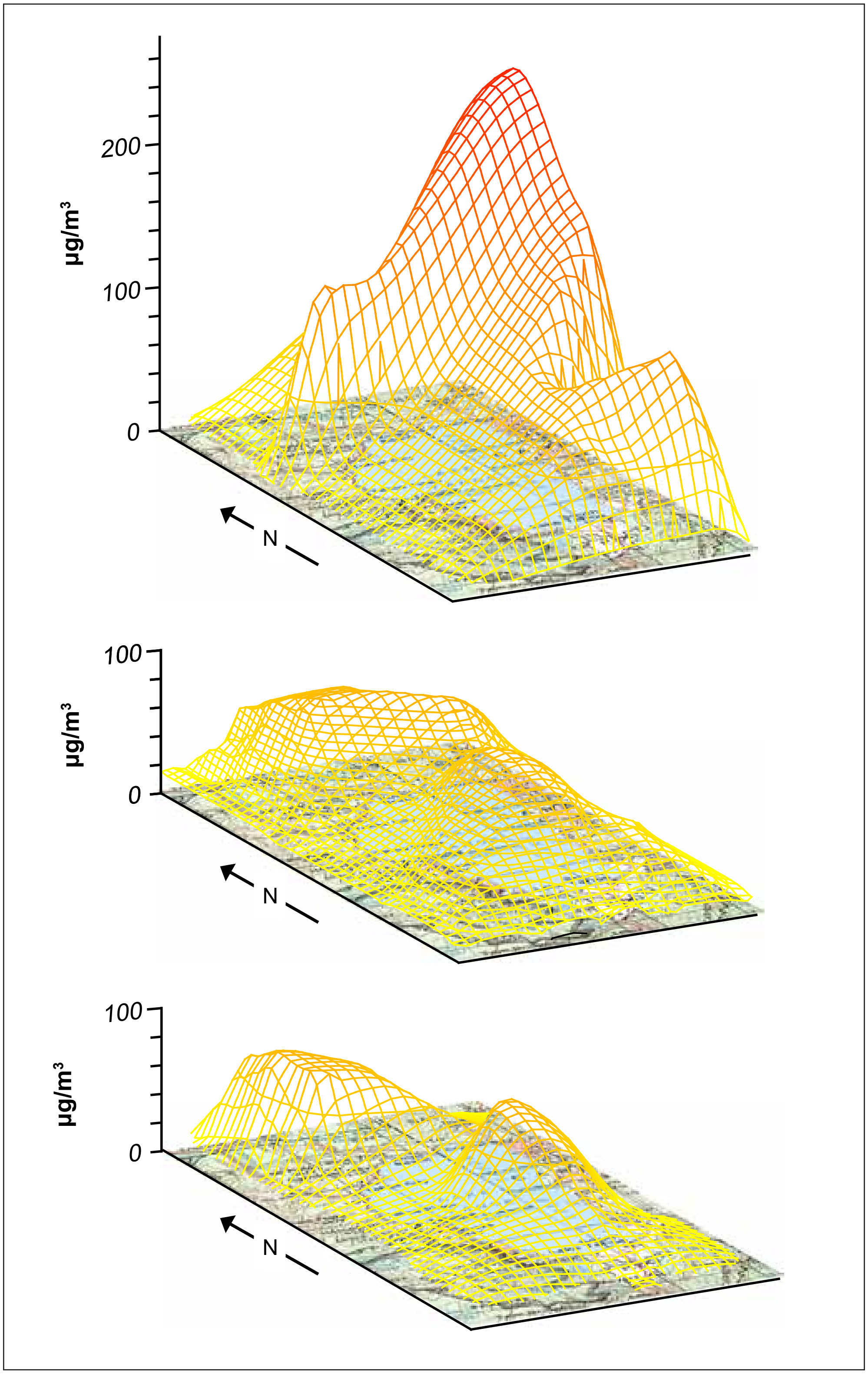

Figure 3.6—Example of Lake Tahoe Atmospheric Model prediction of the evolution of $PM_{2.5}$ from forest fire smoke for 3 days during the Ward Creek prescribed burn. The z-axis represents $PM_{2.5}$ concentrations in µg/m^3. The bottom graph is day 1 and the top graph is day 3.

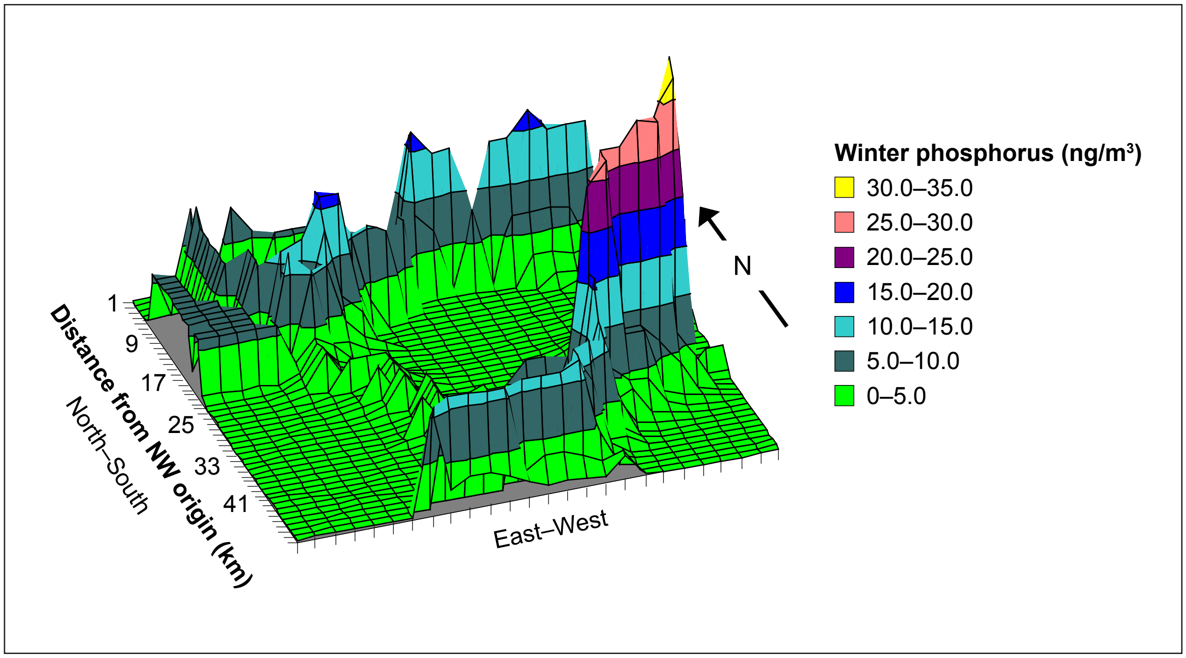

Figure 3.7—Lake Tahoe Atmospheric Model extended to include phosphorus concentrations (ng/m^3) around and over Lake Tahoe. Courtesy of UC Davis Delta Group.

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 19^{th} 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 µg/m^3) and proposed (35 µg/m^3) $PM_{2.5}$ mass standards (fig. 3.8).

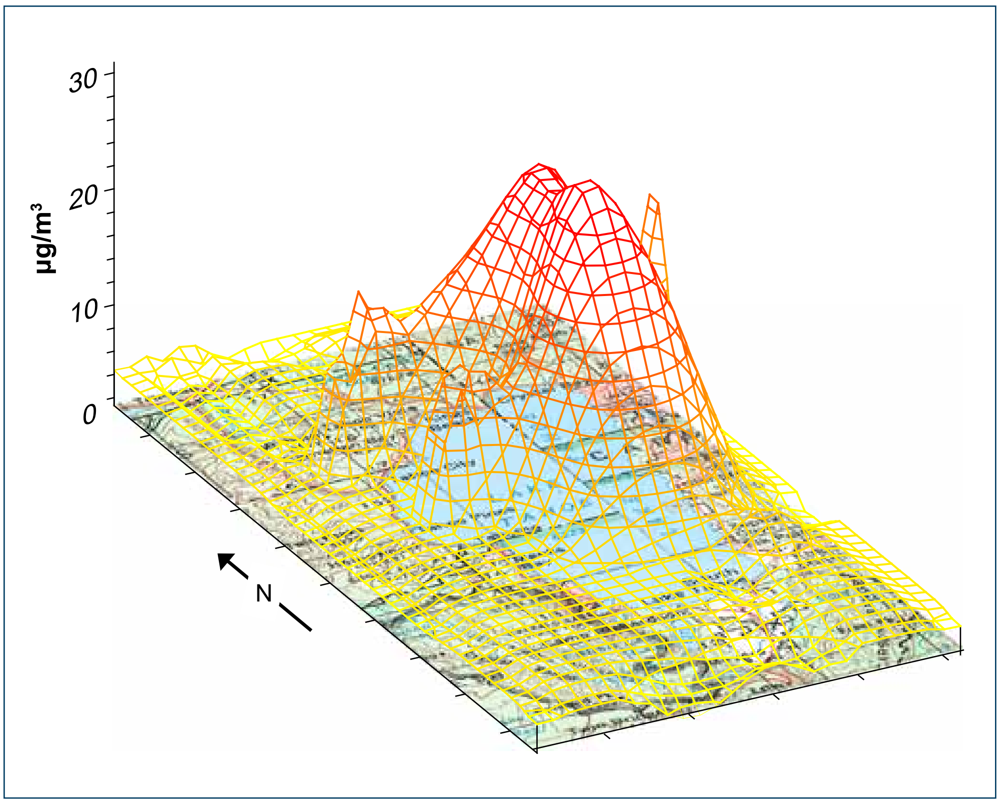

Figure 3.8—Lake Tahoe Atmospheric Model output for $PM_{2.5}$ concentration distribution (µg/m^3) in the Lake Tahoe basin (underlying map) from historical fire situation based on a 24-hour average.

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 µg/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.

Scott Hinton

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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