CHAPTER THREE
AIR QUALITY

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Introduction

Lake Tahoe resides in a high elevation basin separated from the Sacramento Valley by the dominant Sierra Nevada divide along the Crystal Range. Lower ridges of the Carson Range to the east separate the lake from the Great Basin. These physical attributes define atmospheric processes in the Tahoe basin as much as define hydrological processes. The presence of the cold lake at the bottom of the Tahoe basin determines an atmospheric regime that, in the absence of strong synoptic weather systems, develops very strong, shallow subsidence and radiation inversions at all times throughout the year. In addition, the rapid radiation cooling at night generates gentle but predictable downslope winds each night, moving from the ridgetops down over the developed areas at the edge of the lake and out over the lake itself. Local pollutants within this basin are trapped by inversions, which occur almost nightly in the summer and between storms during the winter, greatly limiting the volume of air into which they can be mixed. This condition then allows pollutants to build up to elevated concentrations. Downslope winds each night move local pollutants from developed areas around the periphery of the lake out over the lake, increasing the opportunity for these pollutants to deposit into the lake itself. This meteorological regime of weak or calm winds and a strong inversion is the most common atmospheric pattern at all times of the year (Cahill et al. 1989, 1997).

The location of Lake Tahoe directly to the east of the crest of the Sierra Nevada Mountains creates the second most common meteorological regime, that of transport from the Sacramento Valley 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 to the Sierra crest and over into the 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 becomes 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 from upwind sources in the Sacramento Valley.

Other meteorological regimes at Lake Tahoe are defined by strong synoptic patterns that overcome the dominant terrain-defined meteorological regimes of local inversions, nighttime downslope winds, and valley transport. These include winter storm regimes that bring almost all the precipitation received by the basin, mostly in the form of snow. Winter storms have strong vertical mixing, diluting local and upwind pollutants to low levels while bringing in air from the very clean North Pacific sector, accounting for the fact that snowfall within the basin has a relatively low concentration of anthropogenic pollutants, such as nitrates and sulfates (Laird et al. 1986; Cahill et al. 1997). Another important pattern is associated with the basin and range lows that during the summer circulate 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 basin. The inversion-based basin trapping collects local sources, such as vehicular, urban, and forest burning emissions. Furthermore, these inversions, even if weak, limit the air into which

pollutants can be mixed, thereby raising them to significant levels. Transport of pollutants from the Sacramento Valley increases concentrations of both ozone and fine particulates, such as sulfates, nitrates, and smoke, from industrial, urban, vehicular, agricultural, and forest sources in western slopes of the Sierra Nevada, Sacramento Valley, and the San Francisco Bay Area. In the winter, the basin is decoupled from the Sacramento Valley but participates in the synoptic winter storms, generally from the North Pacific, which bring most of the precipitation into the watershed in the form of snow but along generally clean transport trajectories. The basin and range lows bring in air from a very clean sector of the arid west as do the Northwest highs with their strong dry winds (Malm et al. 1994).

Historical Conditions

Natural lightning fires and fires set by the Washoe people produced smoke in the Lake Tahoe basin in historic times. The analyses of Tahoe basin fire return frequency of the Sierra Nevada Ecosystem Project (Cahill 1996) indicate a fire return frequency of roughly 30 $\pm$ 10 years, resulting in roughly three percent of the basin being burned each year; less frequently on the western side, more frequently on the eastern side. This results in fires covering on the average approximately 25 acres per day every day during a fire period from May through October. However, this is also the time of the year that strong upslope mountain winds clean out the basin each afternoon, so that the smoke was not carried over day to day.

Even in the absence of smoke from fires, some haze would have been present, as the sun volatilizes light-scattering terpene aerosols from the forest during the summer. The logging associated with the Comstock Era also undoubtedly resulted in smoke from fires and steam engines (Elliott-Fisk et al. 1997). However, other than wood smoke and natural aerosols, there was little to affect air quality in the basin until the urbanization of the last forty to fifty years.

In the 1960s, human population levels increased and more people began to live in the Lake Tahoe basin year-round. Single-family housing units in particular rose from only a few thousand in 1950 to many tens of thousands today, each requiring soil disturbance for construction, support services, and road access, wood for fireplaces, and all the necessities of habitation. Urbanization and the various and widespread basin recreational opportunities generated substantial vehicular traffic. Human occupants of the surrounding mountain landscapes and those of the basin led to inputs from wood-fueled stoves, dust, and other particulates from upwind and in-basin areas. As early as 1963, a team of expert scientists studying the water resource problems of Lake Tahoe for the Lake Tahoe Area Council (LTAC) said that atmospheric deposition of the algal nutrients phosphorus and nitrogen should be considered a major component of the lake's nutrient budget (McGauhey et al. 1963).

In 1972, a spot check of carbon monoxide and fine particulate (i.e., automotive) lead showed high values in the city of South Lake Tahoe. In response, a study was undertaken in the summer of 1973 by the California Air Resources Board (CARB) at 10 sites around the lake and nearby (CARB 1974). The results confirmed the earlier study, showing levels that reached or surpassed those seen in many cities for primary automotive pollutants (Cahill et al. 1995). This study resulted in the Lake Tahoe basin being designated as a separate air basin by both California and Nevada, with very stringent standards on carbon monoxide (because of the high elevation) and on visibility (because of the scenery). Regular monitoring of pollutants commenced at South Lake Tahoe in 1976, along with studies by the UC Davis Air Quality Group (AQG) in (Cahill et al. 1977). The AQG studies and work by the CARB clarified the nature of the inversions and basin transport. The AQG performed the first analysis of the fraction of pollutants transported into the basin (ozone, sulfates) versus local anthropogenic sources (carbon monoxide, nitrogen dioxide, lead, most coarse particles) and natural sources (half of the methane, other hydrocarbons). With the CARB monitoring, these studies documented dramatic levels of pollutants that occurred in winter under strong

inversions at both the southern and northern ends of the lake.

In 1978, the US Environmental Protection Agency (EPA) designated portions of the Lake Tahoe air basin as a nonattainment area for carbon monoxide. Meanwhile, residential development added many new homes during the 1970s. The popularity of wood heaters, coupled with the availability of inexpensive firewood, increased wood smoke emissions dramatically during cold weather months. In 1979, scientists from EPA's Las Vegas laboratory conducted sophisticated measurements of visual range in the Lake Tahoe basin and established a baseline condition that still is used today. As the concern for environmental quality, clean air, and clean water grew both nationally and in the Lake Tahoe basin, many pointed to the automobile as the source of the Lake Tahoe basin's air quality concerns. References to smog at Lake Tahoe caused by high levels of traffic inside and outside the basin were common in the literature of the time, and automobiles and wood smoke continue to dominate air quality concerns (Elliott-Fisk et al. 1997).

In the late 1980s analysis of particles in the air improved dramatically after TRPA installed two state-of-the-art particulate samplers, identical to those used in the IMPROVE network of EPA and the National Park Service, under contract with AQG. Optical equipment (cameras and devices that measure light scattering and absorption) at the particulate sampling stations gave scientists the ability to look simultaneously at particulate matter and its impact on visual range. Based on CARB sampling (CARB 1974) and Rice's studies (1988, 1990), sites were chosen at D. L. Bliss State Park near Emerald bay to represent materials coming across the mountains from the Sacramento Valley and at South Lake Tahoe, to represent local in-basin sources. As with the earlier studies, the Bliss site represents the average pollutant levels present across the entire air basin, on which are superimposed the local pollutant sources from urbanized areas around the lake, especially at the northern and southern ends. When the two concentrations are the same, then pollutants can assume to be transported from outside the basin. This situation is the case for fine sulfates. The difference between the Bliss data and the South Lake Tahoe data then represents local contributions to pollution.

While great progress was made with analysis of particles in the atmosphere and their effect on visibility, relatively little progress was made on understanding gaseous pollutants, other than trend data at the sole CARB monitoring site in South Lake Tahoe. Thus, most of the data on gasses around Lake Tahoe must be derived from the summer 1973 CARB studies scaled to trend data from South Lake Tahoe. Nevertheless, these trend data have proven very important in resolving questions of atmospheric inputs to degrading lake clarity, in that they show a steady decline in ambient nitrogenous gasses NO, NO_2, and NO_x.

Current Status of and Trends in Air Quality at Lake Tahoe

The current status of air quality at Lake Tahoe is, by most urban standards, very good to excellent. Few if any violations of state and federal air quality standards for gasses and particles have occurred in many years (Section 3.7.3). The problem with this is that Lake Tahoe is a unique and scenic location with a nutrient-sensitive lake that makes up much of the high elevation basin, which is not a typical urban condition. For this reason, Lake Tahoe was made into its own air basin by California and Nevada in the 1970s and was provided with air quality standards better suited to this unique site. These new standards included a reduction in the California CO standard from 9 parts per million (ppm) to 6 ppm, in recognition of the increased importance of CO to human respiration at high altitude. New standards also included increasing the California visibility standard from 10 miles (16 km) to 30 miles (48 km). The visibility standard then was matched by Nevada. Additional basin-specific standards were enacted in response to the 1981 EPA basin carrying capacity analysis, including CO reductions and visibility thresholds.

Gaseous pollutant data from Lake Tahoe are largely derived from the CARB summer 1973 profiles and the CARB monitoring site, 1977 to the present, in South Lake Tahoe (SLT). The pollutants

for which data are available include carbon monoxide (CO), which is a primary pollutant derived from vehicular and combustion sources (two SLT sites), nitric oxide (NO), which is a primary pollutant derived from vehicular and combustion sources, nitrogen dioxide (NO_2), which is NO modified by atmospheric oxidation, and oxides of nitrogen (NO_x), which include both NO and NO_2, hydrocarbons, methane (CH_4), derived from natural and combustion sources, nonmethane hydrocarbons (NMHC) from both natural and automotive sources (CH_4 and NMHC available from the 1973 study only), ozone (O_3) which is a secondary product of NMHC, NO_x, and sunlight, and sulfur dioxide (SO_2), a primary combustion product (for which some data exist from 1977 on). The analyses of University of California Davis (CARB 1979-1994) and all subsequent work indicate that all of these pollutants are overwhelming anthropogenic and local in origin, with the exceptions of methane (which is half natural, half local anthropogenic) and ozone (which is > 90 percent transported from anthropogenic upwind sources).

All of these pollutants are presently well below state, federal, and basin air quality standards, and all except ozone continue to decrease based on improved fuels and vehicular engines (CARB 1999). The steady increase in ozone at Lake Tahoe from 1977 to the present is unique in all of California. For all other urban sites with 20 years of data, ozone has declined. The result is that ozone is rising to levels close to the state and the proposed new federal standard, which is presently on hold due to court rulings. It is also close to levels at which chronic ozone damage to vegetation could become more serious than the present light to moderate injury levels (Cahill et al. 1997).

Ozone concentrations are highest during the summer, when sunlight drives the chemical processes that create ozone from airborne hydrocarbons and oxides of nitrogen. Two factors puzzled scientists. First, the Lake Tahoe basin's highest ozone concentrations were observed in the late afternoon, early evening, and at night, but not closer to solar noon when one would expect them. Second, despite a decrease in emissions of oxides of nitrogen in the basin (again, a result of the cleaner vehicles), ozone concentrations did not decrease. These two factors led air pollution experts to suggest that ozone was, in fact, being transported into the basin from upwind areas (Cahill et al. 1977). Although the basin generated its share of biogenic and anthropogenic ozone precursors, the resulting ozone was probably appearing somewhere downwind in Nevada.

The particulate pollutants for which data exist were derived from the CARB study of 1973, UCD/CARB studies in 1977 and 1979, data from the CARB South Lake Tahoe site 1977 to the present, and the intensive TRPA particulate monitoring at SLT and Bliss State Park (BLIS), 1988 to the present. The latter two together are designated TRPA. Data exist for several pollutants, including total suspended particulate (TSP) mass of particles below 30 micrometers diameter (from 1973 CARB and SLT 1977 to 1987), inhalable particulate matter (PM_{10}) mass (from 1977 to the present, SLT and 1988 to the present, TRPA), and fine particulate ($PM_{2.5}$) mass (from UCD/CARB 1977 and 1979 and 1988 to the present, TRPA). The mass is made up of the following major constituents (roughly in order of importance):

Organics	OC	Organic carbon (1988 to the present, TRPA);
Sulfates	SO_4	Sulfates, generally ammonium sulfate (UCD/CARB 1977, 1979; 1988 to the present, TRPA);
Soil	Soil	Crustal soil-derived particles, especially coarse modes (UCD/CARB 1977, 1979; 1988 to the present, TRPA)
Nitrates	NO_3	Nitrates, generally ammonium nitrate, (1988 to the present, TRPA). Note: also gaseous nitric acid under certain conditions (unmeasured).

The mass includes minor and trace constituents useful in identifying sources. While there are scores for these, the most important include the following:

Lead	Pb	Primary automotive emission (1973 CARB; UCD/CARB 1977, 1979; CARB SLT 1977 to the present; TRPA, 1988 to the present);
Biomass smoke	Knon	Tracer of wood and grass smoke, derived from fine potassium (UCD/CARB 1977, 1979; TRPA, 1988 to the present);
Zinc	Zn	Urban effluent from combustion (UCD/CARB 1977, 1979; TRPA, 1988 to the present);
Selenium	Se	Selenium from industrial combustion of sulfur containing fuels (coal, oil) (TRPA, 1988 to the present).

By 1994, TRPA air monitoring had clearly defined the ratio of local-to-transported particulate matter and had coupled it closely to visibility degradation (Molenar et al. 1994). In the summer, roughly half of the $PM_{2.5}$ particles are of local origin, and half are transported from upwind sources on the western slopes of the Sierra Nevada, the Sacramento Valley, and the San Francisco Bay Area. In the winter, most of the particulate pollutants are local.

Effects of Air Pollutants at Lake Tahoe

The uniqueness of Lake Tahoe naturally leads to complexity in air quality concerns relative to typical urban air basins. These complexities often allow one to lose sight of the sweeping general concepts into which the detailed concerns are imbedded.

Air quality is adequate when it does not materially degrade the Lake Tahoe ecosystem, including its human component. Thus, what may be considered good air quality in many monitored locations may be disastrous at Lake Tahoe. To aid in maintaining perspective, air quality questions can be summarized as follows:

- Does air quality limit how far one can see through the air?
- Does air quality limit how deep can one see into the lake?
- Is air quality adequate to protect the forest?
- Is air quality adequate to protect human health?

Each of these questions is designed to address a particular set of ecological and societal values of Lake Tahoe, and the loss of which would degrade the entire system. To see this, consider the hypothetical consequences if the answers to the above questions turn out to be affirmative:

- If visibility is poor, one of the world's great scenes is degraded, and tourists go elsewhere.
- If the lake is cloudy and mats of algae float on it, the ecosystem is degraded and tourism suffers.
- If the forests are devastated by ozone damage and they are full of dying trees, the scene is degraded and the chance for catastrophic fires increases.
- If people who come to Lake Tahoe suffer from carbon monoxide or ozone and high fine particle impacts that make breathing difficult, visitors will stop coming, and local residents will suffer.

Visibility

Visibility reduction is dominated by fine particulate mass. In 1991, TRPA reported that the five major constituents of visibility-reducing aerosols in the basin were, in order of their mass, organic carbon, water (bound to particles, especially sulfates and nitrates), soil, ammonium sulfate, and ammonium nitrate. The air samplers collected small concentrations of industrial metals, which are indicators of industrial sources that are not present in the basin (TRPA 1991). The findings were expanded and published (Molenar et al. 1994) and showed that for both regional (lakewide) and subregional (South Lake Tahoe), the visibility has steadily degraded.

The regional visibility is dominated by transport from upwind sources, especially organic matter (smoke), sulfates, and nitrates. The largest

concentrations of these components occur in the summer, when long-range transport conditions are most likely. Ammonium sulfate is an industrial emission pollutant, with only minor sources (diesel, fuel oil combustion) in the Lake Tahoe basin. Ammonium nitrate (mostly from automobiles, generally upwind of the basin in summer and local in winter) represents only six percent of the fine particulate mass. From these measurements, scientists have been able to draw two conclusions: long-range transport of pollutants from distant urban and industrial sources is definitely occurring, and automobile exhaust is only a small contributor to haze and diminished visual range in the basin.

The local visibility degradation is dominated by wood smoke, with nitrates and fine soil particles contributing especially in winter. These local urban plumes appear to extend a few miles over the lake, carried on the weak downslope winds each night.

Contribution of Airborne Pollutants to the Decline in Lake Clarity

In the 1980s, those working to understand water quality trends in Lake Tahoe took a renewed interest in airborne algal nutrients (especially phosphorus and nitrogen). Since the 1963 LTAC study (McGauhey et al. 1963), airborne nitrogen and phosphorus compounds have been recognized as significant components of Lake Tahoe's nutrient budget. 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 is unclear at this time.

In 1981 and 1982, the staff and consultants working on TRPA's threshold standards contacted air quality experts throughout the country and asked what loading rate, in kilograms per hectare per year, of nitric acid one might expect to see in the Sierra Nevada. Based on the responses, they estimated an annual dissolved inorganic nitrogen (DIN) load to the surface of Lake Tahoe on the same order of magnitude as the loads coming from surface streams and ground water 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 cultural eutrophication and to shed light on the sources, distribution, and impacts of airborne pollutants.

In the years following TRPAs nutrient budget study, both water quality and air quality specialists attempted to measure or model nitrogen and phosphorus inputs to Lake Tahoe, with variable and sometimes contradictory results. In 1985, a vital record of nitrate and phosphorus deposition was initiated by the Tahoe Research Group at two sites in the Ward Valley and throughout the basin, including the lake itself (Jassby et al. 1994). However, because deposition is literally a molecular-level phenomenon, monitoring it directly is difficult. Spatial variation in meteorology within the basin, especially over the lake itself, complicates attempts to measure dry-weather and wet-weather deposition.

In 1990 expert testimony in the case of Kelly v. TRPA, summarized what was known about the atmospheric deposition of nutrients to Lake Tahoe. This testimony proposed that the decline in the lake's water quality was not primarily due to atmospheric inputs, because the dominant nitrogenous species over the lake, NO_2, had been declining for 20 years as the lake got worse (Section 3.7.4, 1d). Particulate nitrogen from upwind areas appeared to be less important. With abundant nitrogen in the system from various ecosystem sources, phosphorus is now the limiting influence on aquatic productivity (see Chapter 4). Soils, especially disturbed soils (e.g., along road cuts), appear to be the largest source of phosphorous, with smoke from wood stoves, agricultural burning, and other combustion potentially being important sources of phosphorus.

Impacts of Air Pollutants on Forest and Human Health

The major documented impact of air pollution of the Sierra Nevada forest is ozone on Jeffery pines (Cahill et al. 1996b). Data from this phenomenon were used to develop a threshold ozone concentration below which damage to the Jeffery pine was minimal. This threshold was based

on concentration multiplied by hours above 0.09 ppm. This level of O_3 is rarely reached at Lake Tahoe presently but will be routinely violated in 10 years if present trends continue.

Surveys of ozone injury to forests in the Lake Tahoe basin (Pedersen 1989) showed only light to moderate impacts, but the characteristic ozone mottle was and is clearly evident, especially on high foliage in the tallest trees. Ozone damage ages the trees, reducing productivity through premature aging of the pine needles, reducing sap flow, and making the tree vulnerable to drought, insect attack, and other stress factors.

The primary impact of Lake Tahoe air pollutants on human health used to be the relatively high carbon monoxide levels of the 1970s. Carbon monoxide concentrations have since been greatly reduced. At present, the high $PM_{2.5}$ levels in the winter in urbanized areas is the major concern. However, a recent study for the American Lung Association (Cahill et al. 1998) showed low impacts on cardio-pulmonary and stroke markers at Lake Tahoe. This same study showed a statistical association with particulate pollutants and ischemic heart disease in other sites in California.

Link Between Science and Policy for the Benefit of Lake and Watershed Management

Air quality is a critical concern for Lake Tahoe watershed management because it is linked in either a major or minor way to nearly every valued resource within the basin. Thus, for management of the watershed and airshed of the basin, there is a need for comprehensively understanding hydrologic, atmospheric, and ecological processes and their interactions, for assessing current environmental conditions (e.g., air quality, water quality, and forest health), for responding to anthropogenic and natural disturbance, and for predicting environmental improvement based on various management strategies (after Reuter et al., this document).

Indeed, serious concerns regarding ecological condition and long-term environmental protection underscore the need to provide the highest quality science to aid in problem resolution at Lake Tahoe. Ecosystem health, sustainable environment, and watershed management are interrelated and are part of the growing view that the fabric of the natural landscape is a complex weave of interacting influences, including physical, chemical, and biological factors. Time after time, valid scientific data, with unbiased interpretation, have provided decision-makers in the Tahoe basin with valuable information and insight. For this reason the Lake Tahoe Watershed Assessment is important to provide a sound scientific foundation to inform the ongoing policy and management dialogue.

A critical component for long-term planning at Lake Tahoe is an air quality model based on the terrain and meteorological setting, local and regional pollutant sources, and the removal mechanisms of deposition and transport out of the basin. This model is important because data on air quality are deficient due to limited measurements in space, time, and component, with large areas of the basin totally unrepresented by data of any sort at any time. Through a heuristic model, these limited measurements can be combined with other data (such as traffic volume changes over time, upwind source profiles, urban patterns of growth, and parallel data from similar sites) to provide a comprehensive model for the basin. Though limited in overall predictive ability owing to the limited data set, this heuristic modeling approach maximizes the ability to predict pollutants, hence to evaluate changes made in human use patterns. Without such a comprehensive model, management actions designed to improve one condition (e.g., forest health by prescribed fires) could degrade another condition (e.g., visibility or human health). This is especially true for the lake's assimilative capacity to receive nutrients and pollutants. The importance of an understanding of air quality with respect to lake clarity lies in the lake's very slow response to the changes in atmospheric and aquatic inputs, which is quite unlike air quality itself. By knowing the causes and effects of air pollutants in the basin, management agencies will be better able to plan strategies in a more quantitative and therefore effective manner. Based on previous and ongoing

research and monitoring, inclusive predictive models for air quality are being developed for the first time in this report.

Watershed Assessment Focus

The unique conditions at Lake Tahoe can make actions that are seemingly harmless elsewhere quite harmful at Lake Tahoe. Lake Tahoe lies in a high altitude basin ringed by large mountains and is downwind of the rapidly developing San Francisco Bay Area and the Sacramento region. The basin contains a very large, cold lake in a small watershed, giving a refill time of roughly 700 years, thus a long memory for insult. The mountainous topography and developmental priorities have put almost all roads and houses close to the water's edge. As a consequence, each night a weak downslope wind pushes air pollutants out over the lake and traps them under a strong and shallow inversion. Thus, these pollutants degrade visibility and are deposited into the lake, enhancing algal growth and loss of lake clarity. The pollutants persist over the lake until they are removed by strong winds in summer, at roughly 11 AM each morning; at other times of the year air pollutants may accumulate in the basin for several days.

All of these factors place severe constraints on acceptable levels of air pollutant emissions. These emission constraints are often unpopular, thus require the very best scientific support to ensure their necessity and efficacy in protecting Lake Tahoe. With this solid scientific foundation, the public will accept constraints as necessary. This is especially true for those actions that protect lake clarity, as the lake recovers slowly from insult. Pollutants deposited into the lake today may have an impact even decades from now. Compare this with visibility degradation, which could be completely cured in days if local and upwind sources are curtailed. Forest health problems are resolved in a time frame somewhere between that of the lake response and visibility, while human health concerns have both a short-term immediate component (carbon monoxide induced shortness of breath) and long-term (loss of lung function and heart problems) effect. This watershed/airshed assessment must then address five critical issues as follows:

- Issue 1. The need to gather discontinuous air quality data at Lake Tahoe into a consistent form through the development of a heuristic model.
- Issue 2. The need to determine and quantify pollution sources by location and type (natural and anthropogenic, local and transported) that result in air pollution at Lake Tahoe.
- Issue 3. The need to determine the effects of air pollution levels, including regulatory and human health impacts, and welfare issues, including visibility, lake clarity, and forest health.
- Issue 4. The need to assess the relative impacts of air pollution sources in the Lake Tahoe basin welfare.
- Issue 5: The need to establish the means by which emissions can be reduced to levels necessary to avoid deleterious effects.

The discussion of these key issues and questions serves a number of important purposes. First, it allows scientists to conduct a comprehensive review of past atmospheric studies in the Lake Tahoe basin. Second, it provides agency and university scientists, policy-makers, interested organizations, and the concerned public with an invaluable document that serves to consolidate our knowledge about the Lake Tahoe basin. Third, the format of the Lake Tahoe Watershed Assessment, based on issues and questions, provides a framework for future research and monitoring. Although the scope of this document may leave out critical components in its assessment of the Lake Tahoe basin, the issue and question format facilitates the focus of the discussion. Fourth, the contributors to this section of the document also have had the opportunity to conduct a number of new analyses. For example, the first winter-time particulate sampling specifically designed to answer questions regarding atmospheric inputs of nutrients to the lake from local air pollution sources has been conducted. Fifth, the efforts of many university and agency scientists are being combined into focused research areas with specific goals to meet agency, public, and academic needs. Finally, the assessment process has

allowed atmospheric scientists to begin the important discussion of air pollution sources and impacts on lake clarity, forest health, and human health in a much more integrative fashion.

The first issue addressed in this chapter, the need for a comprehensive model, is then used to address issues two through four in an integrative manner heretofore lacking in any Lake Tahoe basin report. Because of the previous absence of a predictive model, the generation of a new comprehensive Lake Tahoe Airshed Model (LTAM) will constitute the major portion of this chapter's content, followed by shorter (even terse) application to specific issues. However, on the basis of our collective experience and from extensive conversations with environmental scientists at Lake Tahoe, it is clear that future research and monitoring must address the key data gaps that limit the predictive ability of the model under changing human use patterns. This approach is critical to the future of restoration efforts within the basin.

The Lake Tahoe basin is a small but complicated airshed with both upwind and local sources of pollutants. Because of this complexity, it is highly unlikely that any single mitigation project will have a significant affect on all of the air pollution impacts to the Lake Tahoe basin. A comprehensive approach to science and management based firmly on information contained in this assessment therefore is needed. Furthermore, technical products, such as the LTAM, which will give management agencies in the Lake Tahoe basin a basis for achieving air quality adequate to protect the diverse components of the Lake Tahoe air and watershed, are imperative.

At the completion of the Lake Tahoe Watershed Assessment project a number of significant findings have resulted. First, a comprehensive discussion of air quality in the basin has been undertaken. This discussion elucidates the need for comprehensive focused study of the impact of the atmosphere on the Lake Tahoe ecosystem. Second, air quality data from disparate sources have been collected into a single heuristic tool, the LTAM. A large-scale effort to gather long-term research and monitoring air quality data at Lake Tahoe reveals a significant gap in understanding of the link between air quality and lake clarity. For instance, no published study reports measurements of atmospheric phosphorous to match the deposition study results of Jassby et al. (1994). However, loss of visibility and forest damage from atmospheric pollution is well documented (Molenar et al. 1994; Pedersen 1989). Third, using the predictive ability of the LTAM, prescribed and wildfire scenarios have been evaluated. Finally, a prediction of historical air quality in the Lake Tahoe basin is derived from the LTAM. It appears that historically, wildfires in the basin were small and well ventilated, resulting in local visibility of approximately 20 miles (32 km) and regional visibility of greater than 60 miles (96 km). These visibility predictions are well within the current TRPA standards.

Issue 1: The Need to Collect Discontinuous Air Quality Data at Lake Tahoe into a Consistent Form through the Development of a Heuristic Model

With contributions from Tony VanCuren and Thomas M. Cahill

The uniqueness of the Lake Tahoe basin airshed makes air quality models developed for general airsheds ineffective. The nexus among lake clarity, forest health, visibility, and human health make modeling of this ecosystem particularly challenging. Due to limited knowledge of variable parameters, such as source strength, meteorology, deposition, and often composition, model development is made more formidable. Despite these substantial obstacles, a model that is specific to the Lake Tahoe basin was developed as part of this watershed assessment. This model will continue to be developed as data become available. Furthermore, this airshed model is expected to be integrated with other models developed for the basin.

What is the model that was developed specifically for the Lake Tahoe basin, and what are the sources and reliability of data used for its development?

Information on the air quality at Lake Tahoe is qualitatively available from the mid-19th century, from comments by such visitors as Mark

Twain (1872), and from photographs from the 19th and early 20th centuries, but detailed information dates only from the mid-1970s. Even now, quantitative long-term data are available at only limited sites and times. Air quality data since the 1970s are available from a variety of sources, but no continuous record exists for all air pollutant data.

In designating Lake Tahoe as an air basin, the CARB appreciated the fact that terrain plays a major role in air quality at Lake Tahoe. The tall mountains, cold lake, and terrain that forces roads and development close to the lakeshore all make spatial gradients very important at Lake Tahoe. A number of important processes dominate the sources and transport of pollutants in the basin. Upwind transport, local sources, forest deposition, lake deposition, and transport out of the basin are all major dynamical factors at Lake Tahoe. An overview of the important atmospheric processes are shown in figures 3-1 and 3-2.

For several decades, a limited number of air quality studies in the Lake Tahoe basin have been conducted. The CARB, the California Department of Transportation (CalTrans), UCD, and the Nevada Department of Environmental Protection (NDEP) all have collected and reported data on air quality in the basin. Unfortunately, monitoring stations at Lake Tahoe have been moved or closed over this period, making direct comparison of these data difficult. For instance, CalTrans conducted an extensive traffic study of the California portion of the basin in 1974; data from an equally extensive air quality study were collected a year before. Due to the discontinuity of these data, direct comparison of transportation-related air pollutants is unavailable for the Tahoe basin. Furthermore, because a substantial portion of the sites used to collect air data from the 1973 CARB study (Figure 3-3) have been closed, researchers are unable to compare contemporary traffic data with air quality throughout the basin.

Although a continuous record of air quality data is missing for the Lake Tahoe basin, there are valuable data from a number of sources. Aerosol concentration and composition data are available from a study by CARB/UCD in 1977 and 1979 and from ongoing TRPA/Air Resource Specialists (ARS)/UCD collaboration from 1989 to the present. Gaseous data are available from the 1973 CARB study, NDEP monitoring at Incline (limited data only), and continuous sampling by the CARB at two sites in South Lake Tahoe for approximately 10 years. As of this writing the CARB is planning to close one South Lake Tahoe site and add sites at Cave Rock, Incline Village, a west shore site (probably near Tahoma), and Echo Summit. As part of this monitoring site extension, the South Lake Tahoe site at Sandy Way will be upgraded with a full complement of air quality data. TRPA maintains aerosol sites for monitoring of visibility at South Lake Tahoe and D. L. Bliss State Park. Currently, the Interagency Monitoring for Protected Visual Environments (IMPROVE) program plans to take over the Bliss site for monitoring the Desolation Wilderness as a Class 1 visual area.

Air quality is important to the scenic beauty of Lake Tahoe and its environment. Visibility, biotic integrity, and lake clarity are all highly valued in the basin. Air quality is partially implicated in reducing lake clarity, damaging forests, and in contributing to visibility concerns. The complexity of these problems and limitations in data and theory limit the ability of researchers and managers to gauge present conditions at unmeasured sites and to extrapolate the impacts of future regulatory actions. Therefore, it is important to accurately gauge the level of confidence we have in both measurements and theory, as applied to Lake Tahoe (Table 3-1).

The Lake Tahoe Airshed Model

To address both the gaps in ambient data and the unique qualities in the basin, we developed a model specific to the Lake Tahoe air basin. The USFS LTAM is an Eulerian array of 1248-2.56 km^2 (1 mi^2) cells across the basin encoded on a Microsoft Excel spreadsheet. The domain is 72 km (45 miles) north to south (Truckee to Echo Summit) and 42 km (26 miles) west to east (Ward Peak to Spooner Summit) (Figure 3-4). All but the most southern end of the watershed is taken into account by the model. The LTAM is semiempirical in design and incorporates all available air quality measurements at

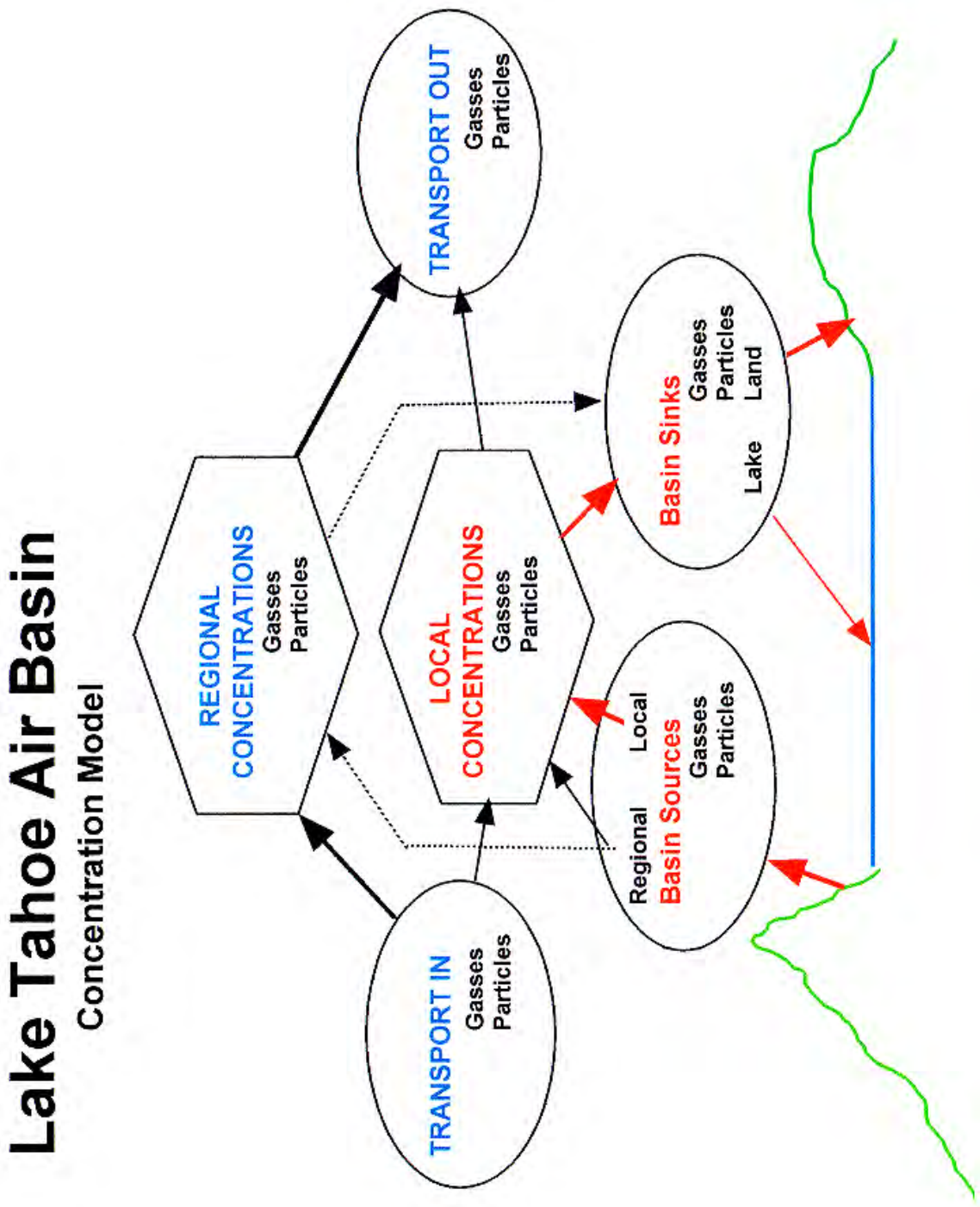

Figure 3-1—Schematic air model for the Lake Tahoe basin, based on concentration of pollutants.

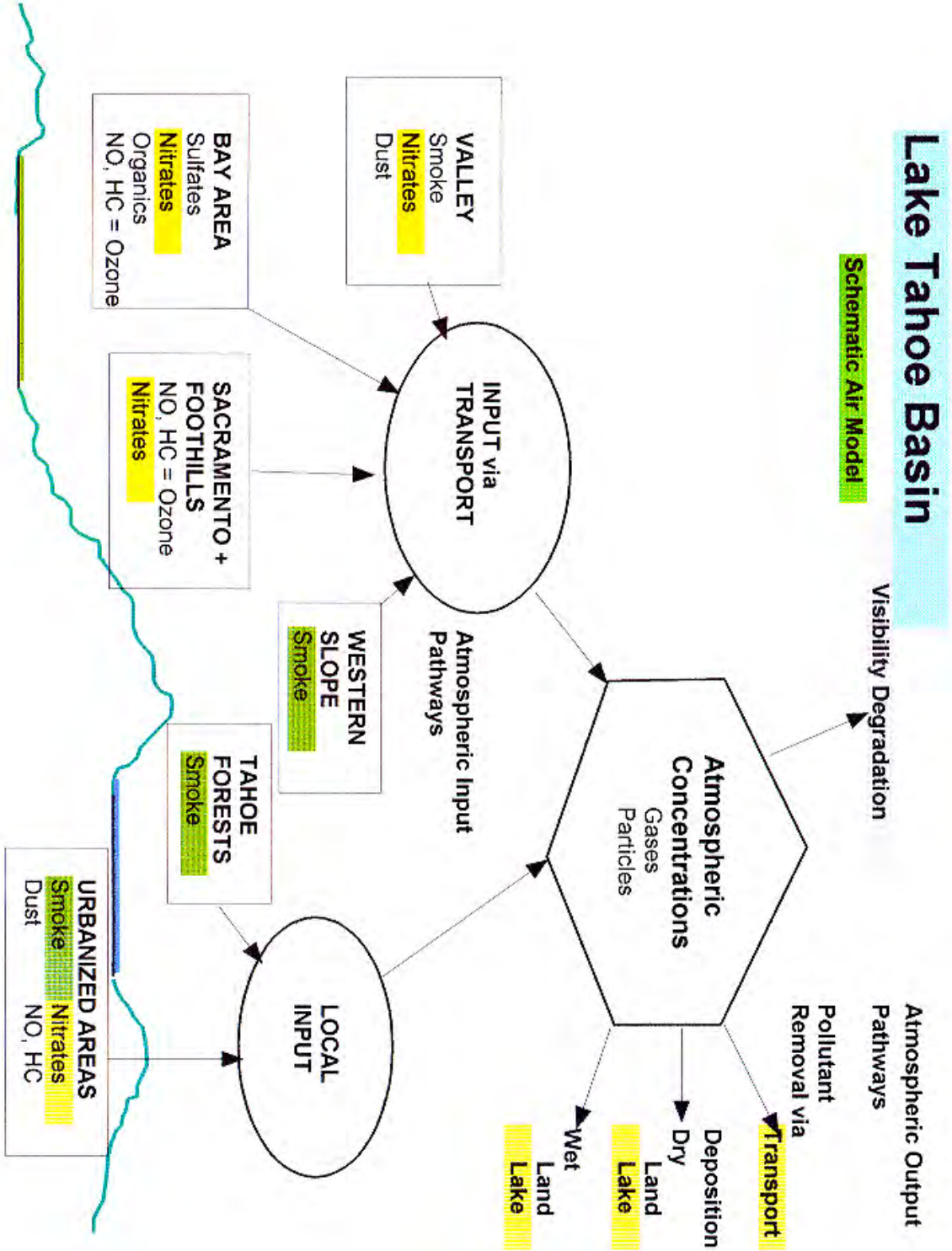

Figure 3-2—Schematic air model (including processes and pollutants) for the Lake Tahoe air basin.

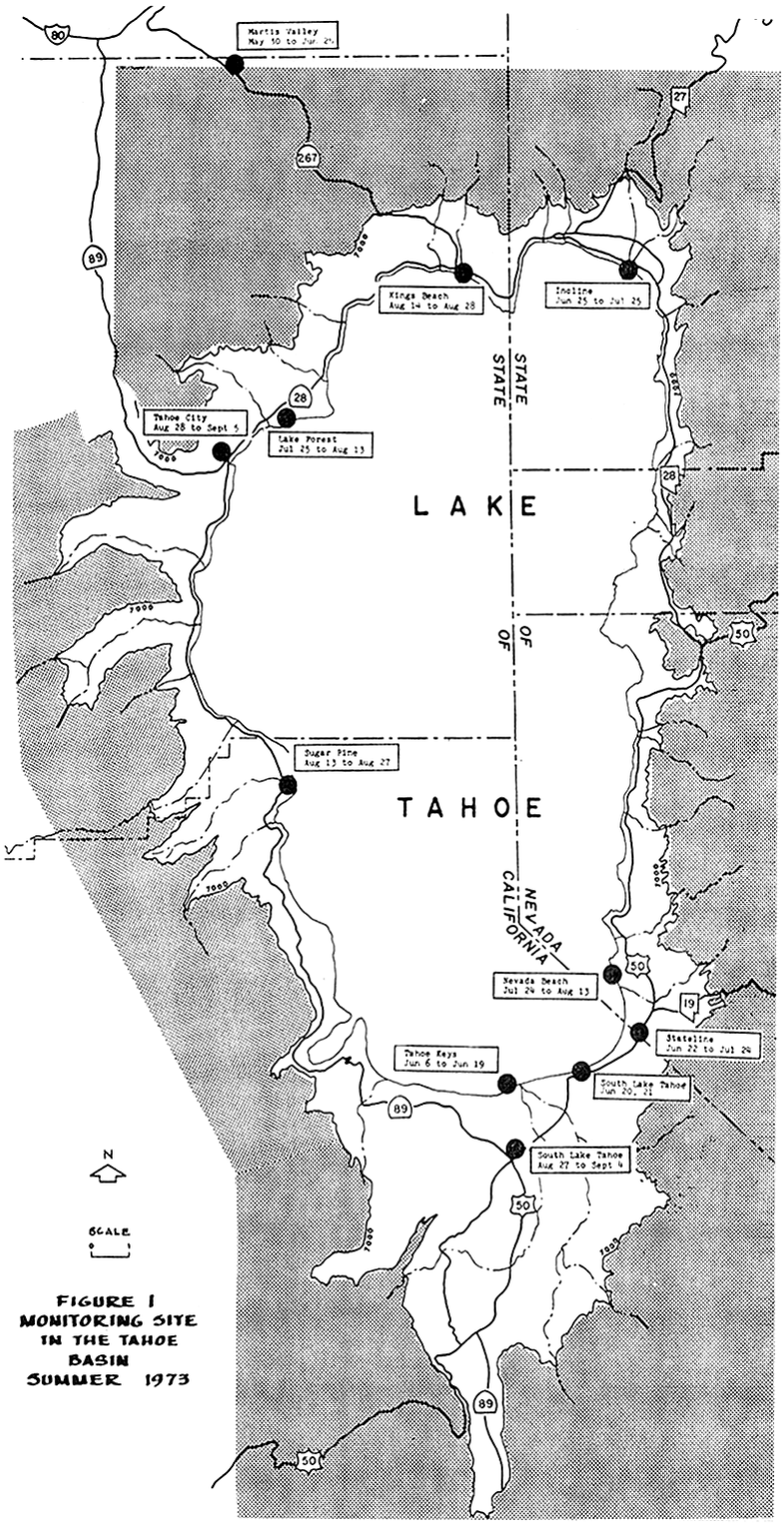

Figure 3-3—Locations of sampling stations used in the 1973 ARB air quality study in the Lake Tahoe basin.

Figure 3-4—Area covered by the Lake Tahoe Airshed Model (LTAM). West to east is modeled from approximately Ward Peak to Spooner Summit and north to south from Donner Lake to Echo Summit. There are 1,248 individual cells that are used for calculating pollutant concentration for this portion of the watershed. This is the underlying map used to display pollutant concentration output from the LTAM results.

Table 3-1—Description of the level of understanding of atmospheric parameters at Lake Tahoe (LT). The five parameters are broken down by scientific knowledge as high, limited, or seriously deficient.

Parameter	High	Limited	Seriously Deficient
Meteorology	SLT	West, NW shores, upwind derived	East, NE shores, ridges
Sources	Upwind (Central Valley, Bay Area)	Local urban, transportation	Area sources, fires (wild/prescribed)
Concentrations and composition			
Gasses	SLT	Rest of LT area	
Particles	SLT	West shore	NW, NE, East
Processes			
Transport	SLT	Rest of LT area	
Deposition		Coarse particles Gasses	Fine particles
Effects	Visibility loss Ozone tree damage	Human health	Lake nutrient effects

Lake Tahoe, 1967 to the present, plus aspects of meteorological and aerometric theory. Free variables, such as traffic flow, acres of forest burned, and population density, are assumed to be linear with pollutant emissions. This model is a heuristic tool used to gather the disparate sources of air quality data at Lake Tahoe into a consistent framework.

The LTAM is a component of the overall Lake Tahoe basin watershed models designed to provide information on the role of the atmosphere in the health and welfare concerns of the Lake Tahoe basin. The construction of this model has two major immediate goals: to identify the relative fraction of in-basin and out-of-basin, natural and anthropogenic components of the atmosphere of the Lake Tahoe basin and to evaluate the effects of atmospheric pollutants in the Lake Tahoe air basin on lake clarity, visibility, human health, and forest health.

The LTAM is designed to be complex enough to include all major components, accurate enough to represent important physical, chemical, and biological processes, and simple enough to allow calculation of results that can be verified by ambient data. In this effort, emission estimates valid in other parts of the state and nation, even if available, may not be relevant to the unique conditions of the Lake Tahoe area. Whenever possible we have used measured values in the basin to establish source emission relationships.

Meteorology

The key parameters that relate to impacts of atmospheric pollutants are source and sink (deposition) strength and meteorology. The meteorological conditions in the LTAM are broken up into summer day, summer night, and winter (nonstorm) conditions. May and early June are considered in the summertime regime. For late September through late October, a combination of the summer day and night and winter meteorological regimes is used. Data on wind speed and direction at the north end of Lake Tahoe are taken from the record at the US Coast Guard pier in Tahoe City. Data at the southern end of the lake are from TRPA data. Mid-lake meteorology is derived from personal observations, enhanced by theoretical interpretation of nighttime downslope patterns seen at the south end of the lake.

Meteorology and topography dominate dispersion downwind from a source. Lateral dispersion in urban settings are calculated from the measured US Hwy. 50 transects (CARB/UCD 1979), while lake transport is estimated from the same parameters modified by the relative z_o obstruction ratio (trees versus a flat lake), giving an estimated one-fifth decrease per grid dimension of 2.56 km^2. This is confirmed by photographs taken in

early winter mornings, showing the South Lake Tahoe haze extending two to five miles over the lake.

Topography is important for the effects it has on the Lake Tahoe basin, especially the development of persistent inversions that trap local pollutants close to the ground. Night winds are assumed to follow topography, moving from the highest points, the watershed boundary, downslope to the lowest elevation, the lake surface. Thus every evening, air is moved from land to water and is trapped close to the water surface. This process tends to maximize deposition to the lake surface, although data confirming this conclusion are lacking.

The model handles meteorology by defining average conditions for seasons and then coding the wind field into each cell by performing an upwind-downwind average along the most prevalent wind direction. For example, the summer day model calculation for west shore meteorology is an average of the three upwind (more west) cells. Further averaging of the meteorological output takes place for summer night and wintertime conditions to approximate the effects of the observed inversions that develop within the basin.

Summer conditions in the basin begin to appear in late May and June and persist into early October. They are characterized by strong differences between day and night, with major transport into and out of the basin during most days. Winter conditions (late October to February) are defined as having no extra-basin transport and persistent inversions. In the spring, strong winds transport fine soil dust both within and from outside of the basin. The choice of these periods was based on the spotty long-term record of meteorology in the Lake Tahoe air basin—primarily the 1967 US Coast Guard station at Tahoe City—to which we added measurements from the South Lake Tahoe CARB site, from the airport (daytime only), and from research studies, especially the 1979 UCD/CARB study, and local personal observations.

For summer daytime winds, the model uses a nominally west to east wind by default, with equal averaging of the three upwind cells (NW, W, SW) to mimic lateral dispersion. Along the northwest (NW) shoreline beyond Tahoe City, the weighting is changed to give a mostly southwest (SW) wind, based on good local data, while the same SW wind is used on the SW lake shore near Tahoe Keys. For nighttime winds, the CARB/UCD 1979 study and South Lake Tahoe data indicate weak terrain winds flowing from high elevations to low elevations at all points. Again, averaging is used to mimic lateral dispersion. For summer nights, the daytime concentrations are retained as pollutants fill the basin and have long enough residence times not to decrease greatly over night. Winter (stagnation) meteorology is very much like summer night, but transported particles are set to zero in the model, and greater cell averaging is used to approximate the effects of the stagnant inversion.

By the time pollutants have traveled to the Lake Tahoe basin, they have become relatively uniform both in the direction of transport (i.e. fall off < 1%/cell) and at right angles to transport (Figure 3-5, ozone and sulfates). Therefore, the LTAM adds this as a source to each cell as would be seen in total background, i.e., no local source, conditions.

For air pollutant emissions from fire, the prescribed fire ambient air data of Cahill (1996), especially from Yosemite National Park, are used. However, these fires are divided into two factors: PF1, in which there is no lofting of smoke (h) ($0 < h < 0.1$ km), and PF2, in which lofting of smoke (h) to greater altitudes ($0.1 < h < 0.5$ km), as observed in prescribed fires with high fuel loading and/or drier conditions (Cathedral burn, October 1998, SNEP Three Rivers, 1995). In these cases, observed ambient concentrations are used rather than mass emission estimates. Fires then are added to the model using one of the following possible settings:

- Prescribed Fire Type 1 (PF1)—the 1992 Turtleback Dome (Yosemite National Park) prescribed fire, monthly average values (Cahill 1996).
- Prescribed Fire Type 2 (PF2)—the 1994 Three Rivers prescribed fire, an example of a large fire.
- Wildfire (WF)—the results the of 1992 Cleveland wildfire at the maximum

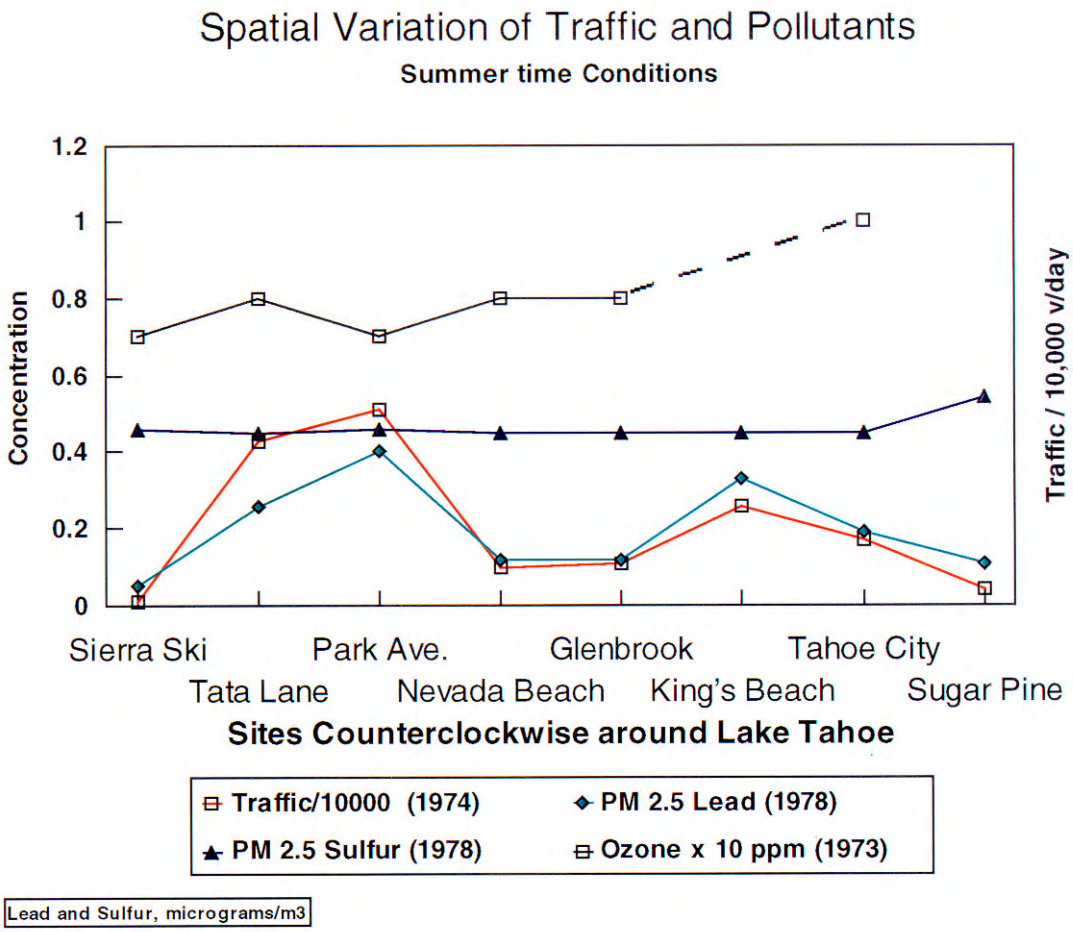

Figure 3-5—Concentration of pollutant and traffic counts for summer conditions at sites around Lake Tahoe.

impact site (Truckee), with chemical composition derived from samples taken at TRPA's D. L. Bliss site.

Model Calculation

Modeling is accomplished by a three-cell average centered on the mean wind direction. This gives a representation of the geographic variability of the wind direction. As sources are encountered, the values are added. Mixing of air from adjacent cells is modeled by mathematical averaging of the meteorological output. This approximates transport of pollutants and mixing within the inversion for the summer night and winter meteorological parameters. Because the winter inversion is so strong and prevalent for a number of days between storms, a greater degree of averaging is performed for the winter calculation.

The falloff of particles downwind of a local line or area source is logarithmic, based on the observed fall off of fine particles at South Lake Tahoe (CARB/UCD 1979). In the prescribed PF1 case, the high correlation between NO_x and lead in the CARB/UCD data allowed adding a generic fine-particle falloff setting to these values. Falloff over the lake, however, should be less rapid due to the much lower surface roughness parameter (z_o) over the water. In the total absence of these data, this parameter is a magnitude of three to five times less than in forest conditions. The values are expressed as the fraction of a pollutant transported into the adjacent downwind cell. Thus, we can use the values

from Table 3-2 for the decrease (D) of pollutants downwind of a source, based on fine particle transport measurements and theory.

Pollutants emitted near ground level, and especially in inversions at night and winter, have been shown to be local in character. While particle removal may play a role, the wind sheer generated in the transition between a forest canopy and the cleaner, faster moving air above it is probably the major factor. Evidence of this was seen in particulate measurements upwind and downwind of Highway 50, in which lead levels (presumably derived from local tailpipe emissions) fell rapidly versus distance, while sulfur levels (presumed to come from long-range transport into the basin) actually rose slightly at the ground level sites, indicating downward mixing of upper level air (CARB/UCD 1979; Figure 3-6).

Upwind pollutant emissions in the basin are derived from the efficient transport between the Sacramento Valley and Lake Tahoe that exists for the summer, typically beginning in April and ending in late October. Sulfate concentrations, which are derived almost entirely from Bay Area refineries and thus represents transported fine particles into the basin, are indicative of this transport effect. The regionality of the transport effect can be further seen in data from Seqouia, Yosemite, and Lassen national parks (Figure 3-7). This effect was investigated through the paired TRPA air sampling sites at D. L. Bliss State Park at Emerald Bay, which represents transported air, and at South Lake Tahoe, which represents both transported and local pollutants (Figure 3-8). An analysis of the annual behavior of transported and local particles (figures 3-8, 3-9, and 3-10) allows upwind sources versus local sources to be estimated (Figure 3-11). A similar analysis of gaseous pollutant data from the 1973 CARB study indicates that NO_x, CO, hydrocarbons, and lead are mostly locally derived and that O_3 is transported (Figure 3-12). These analyses identify very different transport regimes, gasses versus particles, summer versus winter. The model's complexity can be reduced to simplifying observations: all primary gasses (CO, NO, NO_2, NO_x, NMHC, SO_2) are local methane is half natural, half anthropogenic, all secondary gasses (O_3) are transported from upwind sources TSP (0 to roughly 30 microns diameter) is mostly local, and PM_{10} is largely local, $PM_{2.5}$ is entirely local (winter), half local, half transported (summer).

Because sources (sulfates, nitrates, smoke, soil) are far away, the lateral dispersion of wind during transport predicts a uniform distribution of pollutants across the Lake Tahoe air basin. This is in fact observed. The correlation among local traffic, lead, sulfate, and ozone (Figure 3-5), and between soils and road salt (Figure 3-13) indicates that a uniform distribution of transported pollutants exists in the basin and that local sources are quite variable depending on

Table 3-2—LTAM input for decrease in pollutant concentration through dispersion and mixing or loss by deposition per cell (1.6 km) dimension. This describes prescribed fires, wildfires, and long-range transport from upwind. Both forested and over-water areas are given as used in the model. The value D is the relative concentration change per cell in the LTAM. Bold-faced type indicates well-known values as described in text below.

		D_{summer}	D_{winter}
Sacramento Valley source, > 0.95, based on sulfate values measured across the lake		**1.0**	0.9
Pollutant falloff for forested areas:			
PF1	Local source, below tree canopy	**0.40**	**0.15**
Other Local source, below tree canopy		**0.40**	**0.15**
PF2	Local source, just above tree canopy est. from interpolation between PF1 and WF	0.7	0.6
WF	Local Source, far above tree canopy est. from smoke plumes, and	0.96	0.8
Pollutant falloff for over-lake area:			
PF1, PF2, and WF and other local source est. from night time SLT haze		0.9	0.8

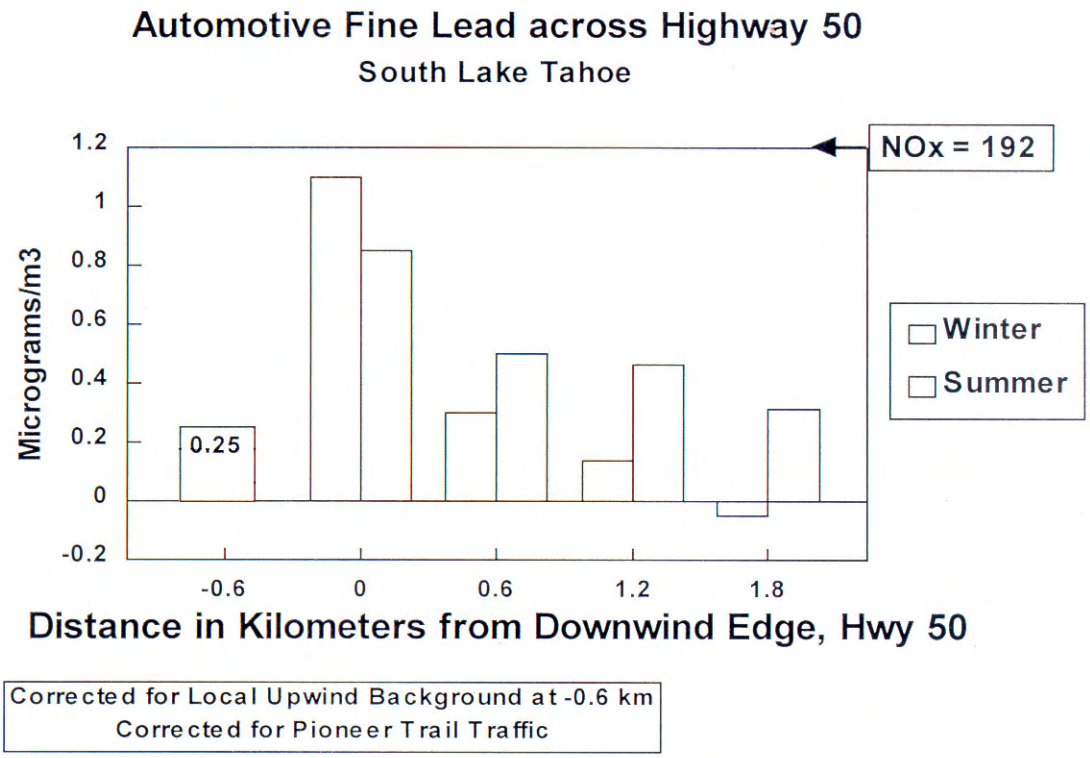

Figure 3-6—Concentration decrease of particulate lead with distance from highway source. This decrease is used to calculate the falloff parameter for PF1 in the LTAM.

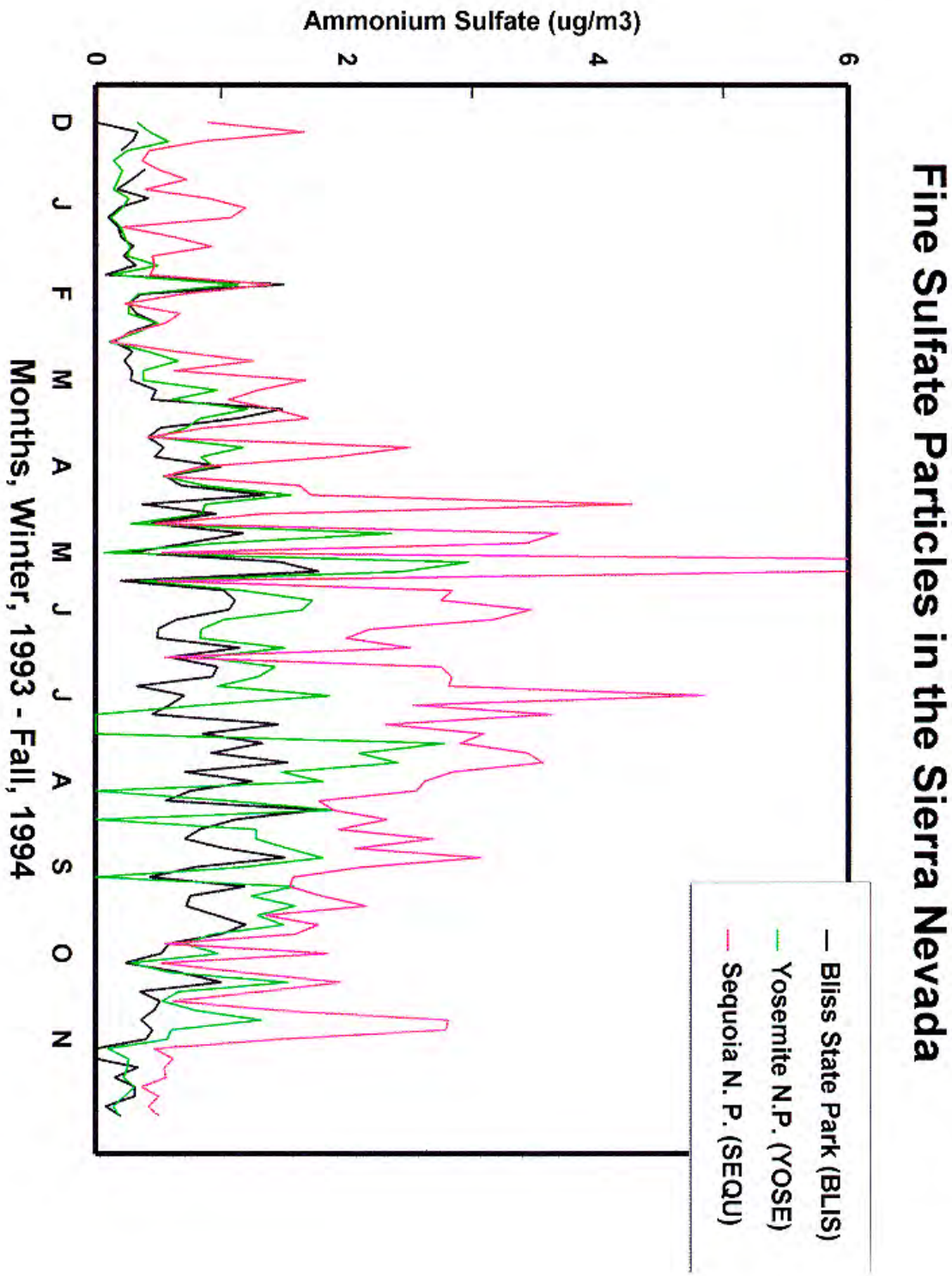

Figure 3-7—Concentration of ammonium sulfate versus time at Sequoia and Yosemite National Park and D. L. Bliss State Park. Note correlation for all three sites.

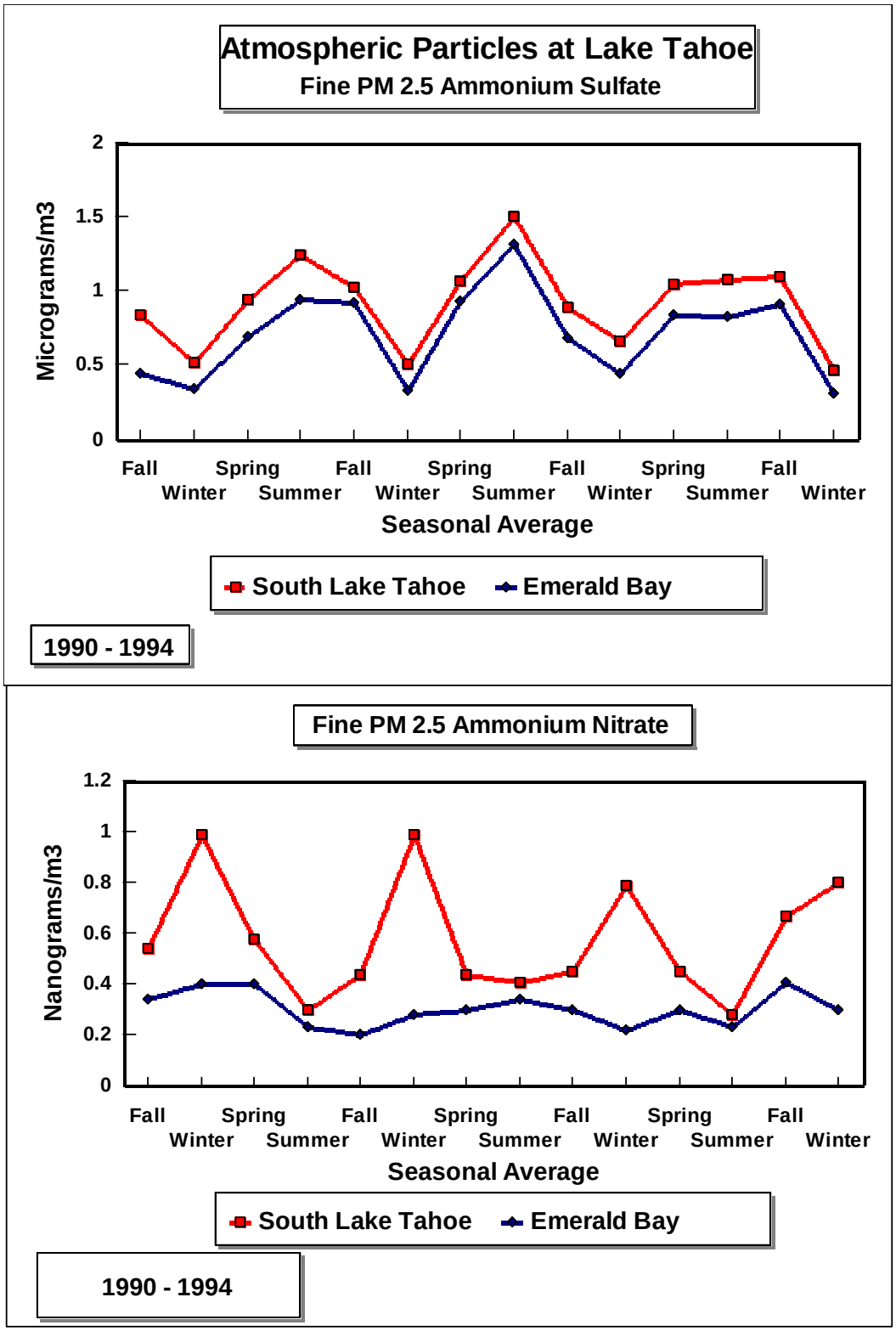

Figure 3-8—Seasonal concentration of $PM_{2.5}$ ammonium sulfate and nitrate at South Lake Tahoe and D. L. Bliss State Park from 1990 through 1994.

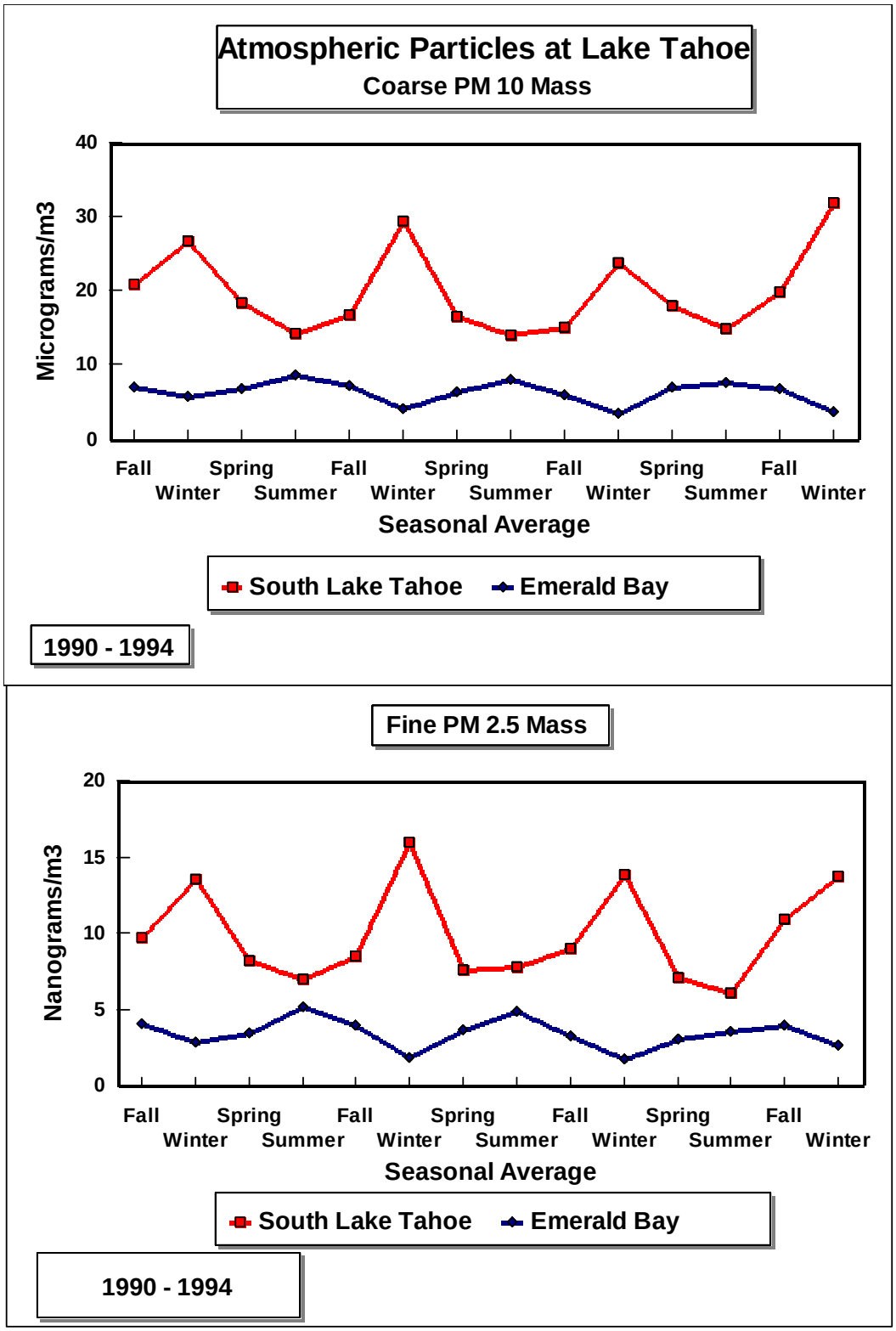

Figure 3-9—Temporal concentration of PM_{10} and $PM_{2.5}$ at South Lake Tahoe and D. L. Bliss State Park for summer and winter from 1990 through 1994.

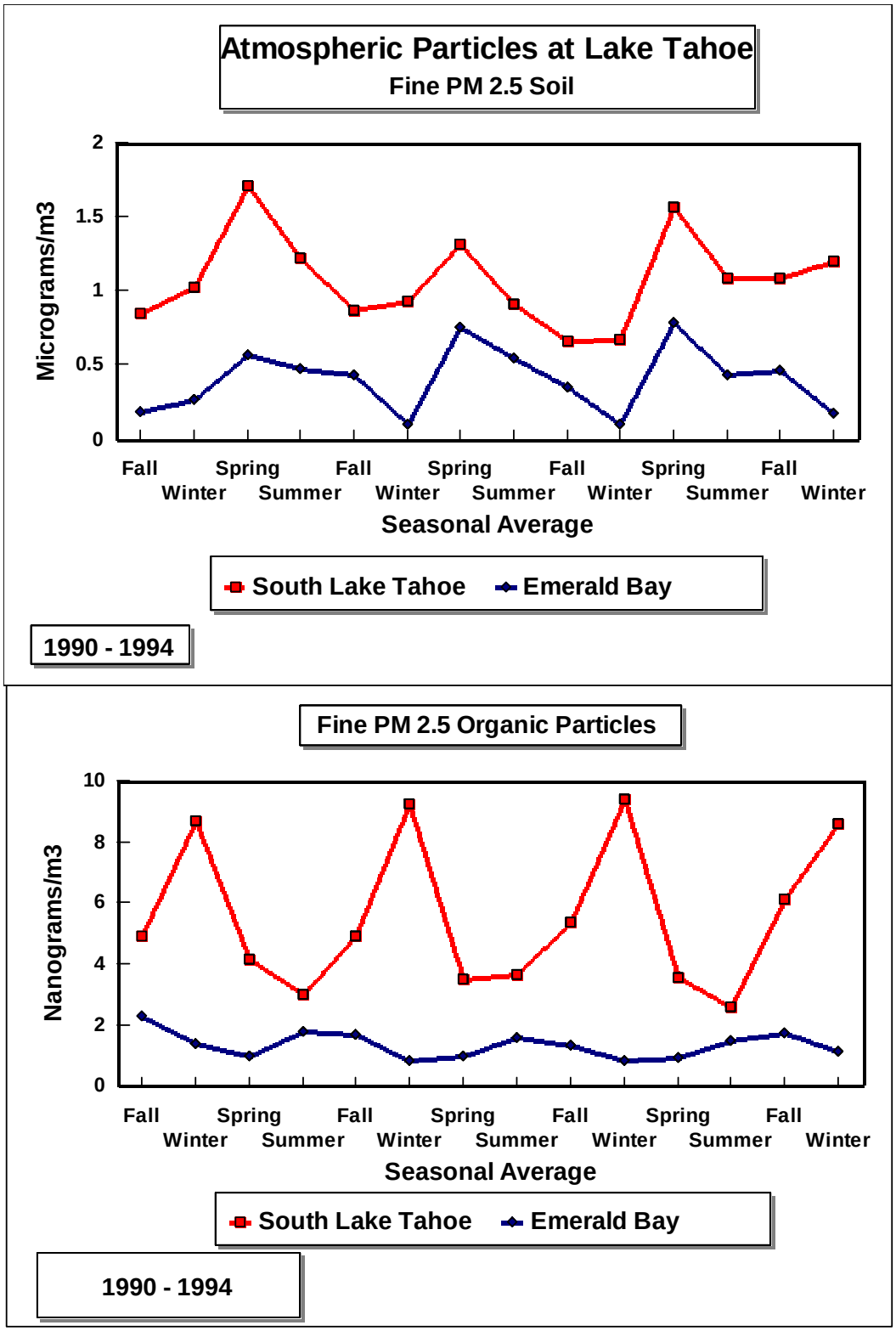

Figure 3-10—Seasonal concentration of $PM_{2.5}$ soil and organic aerosols at South Lake Tahoe and D. L. Bliss State Park from 1990 through 1994.

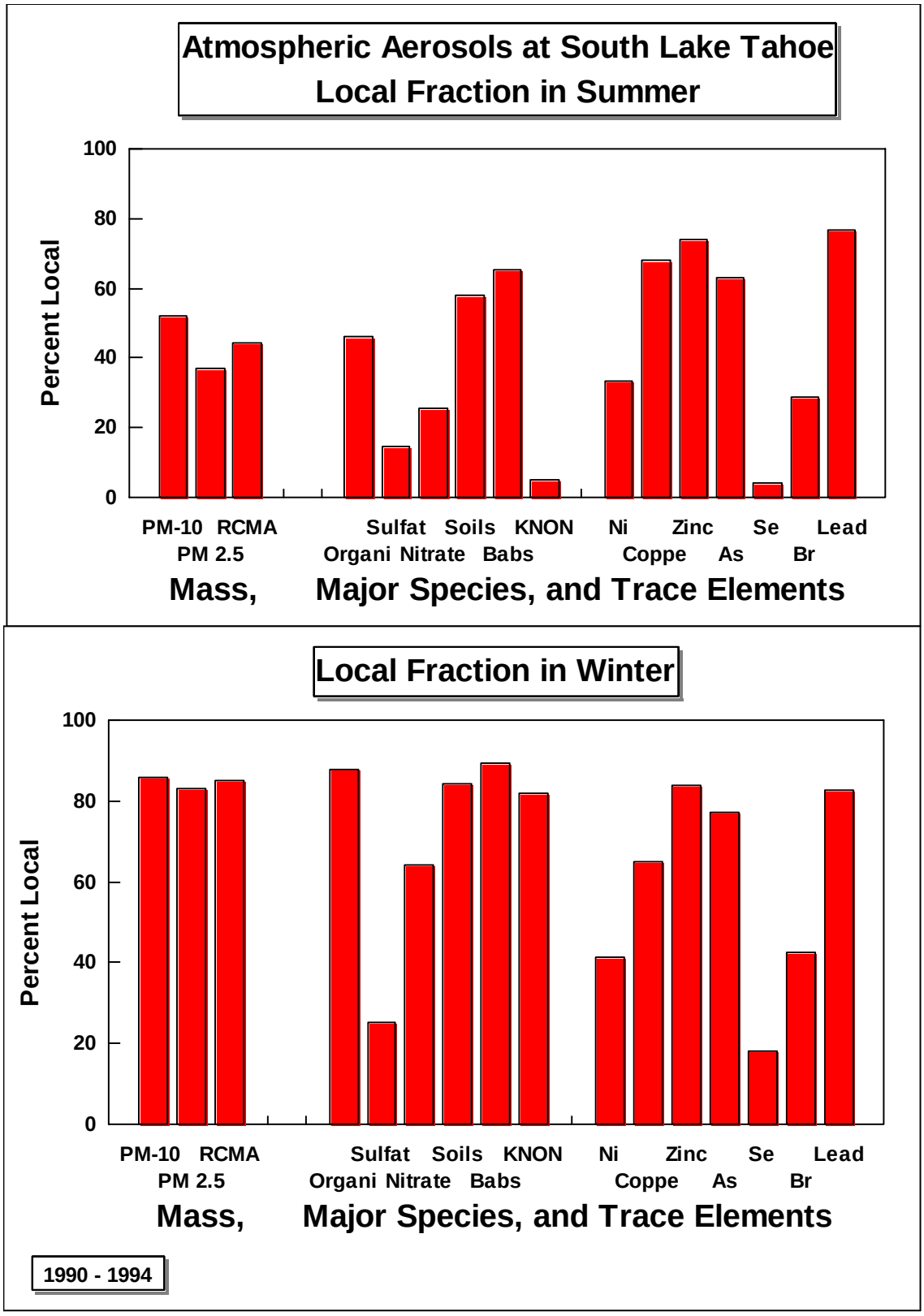

Figure 3-11—Percentage of locally generated aerosol mass and species at Lake Tahoe for the summer and winter.

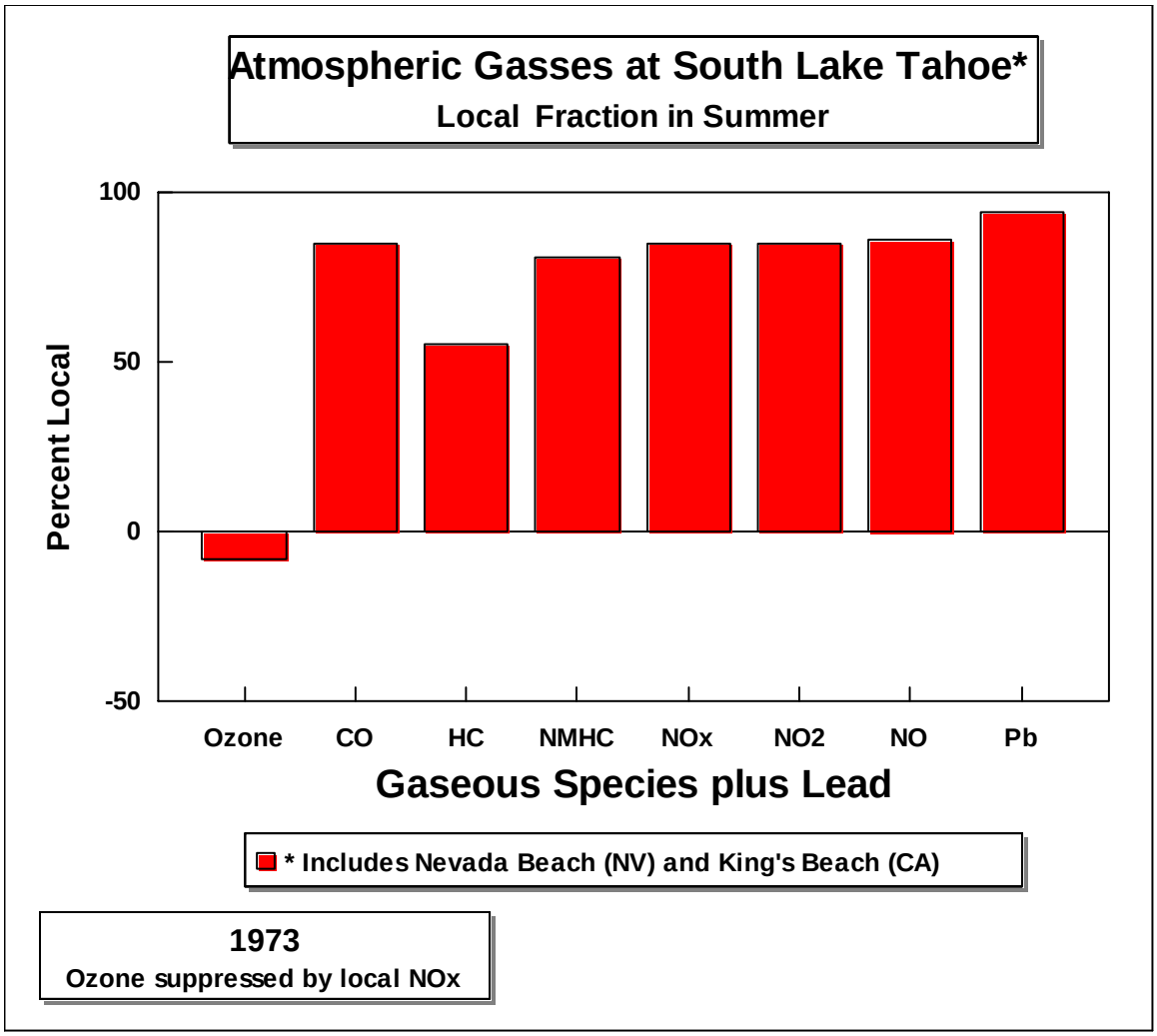

Figure 3-12—Percent of locally generated gaseous (plus lead) pollutant species at Lake Tahoe.

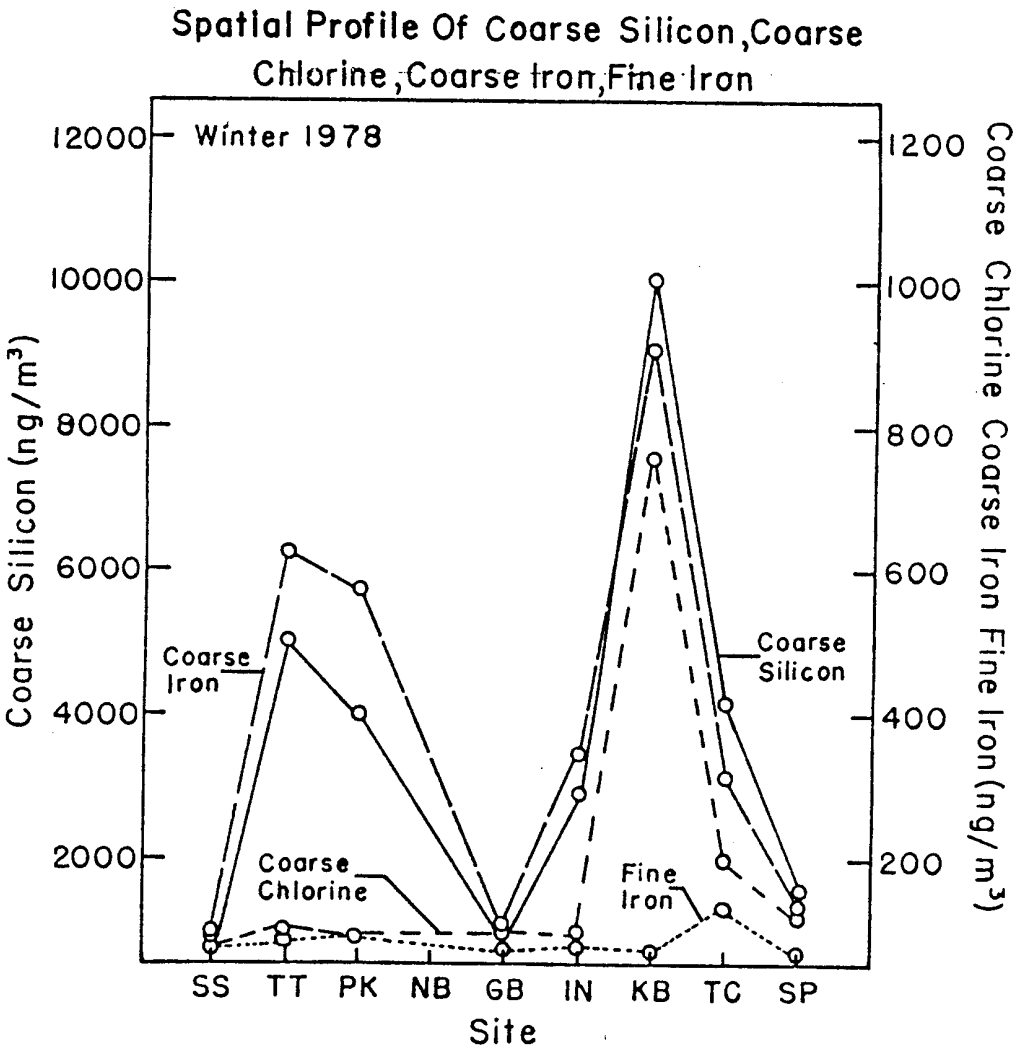

Figure 3-13—Concentration of coarse ($PM_{2.5\text{-}13\,\mu m}$) and fine ($PM_{2.5}$) particles at various sites, from the 1979 ARB/UC Davis air quality study at Lake Tahoe.

source strength. The LTAM, therefore uses a uniform upwind distribution of transported pollutants. An exception is made, however, for near-upwind sources such as prescribed fire, wildfire near the western airshed boundary. These near-upwind sources may not have traveled far enough to become uniform, as shown by the Cleveland fire comparison, Bliss to Truckee, in 1992. (Cahill 1996). Therefore, a second input in the LTAM allows manual input of gradients on a north to south transect. Meteorological measurements, observations of visibility, and calculation shows that most of the mass of transported sources lies in a band between a few hundred feet above the lake to about 10,000 feet (summer, CARB/UCD 1979), thus continue across the basin into Nevada. Local air pollutants are almost always emitted under the strong inversions that dominate Lake Tahoe and tend to stay within the basin. The major exception is forest fire, where the sources can lie well above lake level.

Emission estimates for local traffic are derived from the extensive studies conducted by such entities as CARB and CalTrans during the 1970s around lake Tahoe, which included both air

quality and traffic (figures 3-14, 3-15, and 3-16). These historical data are scaled to present conditions by the extensive ambient measurements at the CARB South Lake Tahoe station, a record that extends back into the late 1970s (see Section 6.1.1). The high correlation between the CalTrans local traffic density counts and ambient lead (Cahill et al. 1977; CARB/UCD 1979; Figure 3-17) allows one to scale other pollutants from the 1973 CARB ambient measurements and the 1974 CalTrans traffic counts. No equally extensive set of traffic and air quality measurements have been made since that time. The local traffic data can then be scaled to air quality ambient measurements, avoiding the complexities of the traffic density-meteorology connection.

The scaling approach is supplemented by limited direct emission estimates from research studies (especially CARB/UCD 1979) with the LTAM "sliding box model" used to connect emissions to ambient concentrations. Finally, traffic is resolved into four categories: heavy (H), with major diesel truck component (I-80), medium-heavy (MH), with considerable diesels in either bus or truck components (Hwy. 50), medium-light (ML) with some diesel and local trucks (parts of Hwy. 89 near Tahoe City, for example), and light (L), consisting almost entirely of cars and SUVs (for example, Hwy. 89 near Emerald Bay). The urban density map of CTRPA, 1976, (Figure 3-18) is used to identify urbanized areas of the Lake Tahoe basin, with some modifications for the growth of specific areas (Glenbrook, Nevada), which were almost totally rural in 1976 but are developed today. The emissions of these areas are then estimated from the South Lake Tahoe - Bliss SP comparisons, summer and winter.

Finally, the LTAM uses an input page to modify variables such as location of point sources (e.g., prescribed fire, forest fire, boats), density of traffic on one of the 26 road segments, transfer rates, and proportional wind velocity (figures 3-19a and 3-19b). A model run example for nitrogen dioxides (NO_x) for a typical summer period is shown in Figure 3-20. For this example, the values in Truckee are estimated at 35,000 vehicles/day because there are no traffic data from the CalTrans study. The output for the model run for traffic from the LTAM (Figure 3-20) preliminarily indicates that Tahoe City is an important source of pollutants in the basin due to the funneling effect of the Highway 89 corridor from Truckee. Further investigation of the importance of Tahoe City is warranted, especially in light of the significant atmospheric contribution of transported nitrogenous pollutants reported by Jassby et al. (1994).

LTAM Model Prioritization

The number of important air quality parameters for model input and output is high even in the limited area of the Lake Tahoe basin airshed. Thus, a ranking of important terms has been determined for the sake of model focus. The ranking we are using is lake clarity, visibility, forest health (biotic integrity), and human health. The first priority is the potential role of air quality as a significant factor in the continuing decline in the water clarity of Lake Tahoe. Atmospheric visibility, the second priority, is clearly dominated by atmospheric contaminants and could be degraded by implementing such programs as increased prescribed fire to improve forest health. Although forest health/general biotic integrity is clearly a major factor in the vitality of the Lake Tahoe airshed, this was given a lower priority because present damage, mostly from ozone, is modest. The potential for future impacts, however, is significant. Furthermore, evidence of loss of biotic integrity due to poor air quality in the Tahoe basin has not been reported. Finally, while the air quality at Lake Tahoe is generally good, there are some actual and future potential violations of state and federal human health-based air quality regulations.

Each of these ecosystem impacts then can be matched to the most important of the many atmospheric pollutants that contribute to the effect:

- Lake clarity:
  - Nitrogen, gasses, and particles
  - Phosphorus, particles
  - Fine soils, particles
- Air clarity:
  - Organic compounds
  - Nitrates, particles
  - Sulfates, particles
  - Fine soil, particles

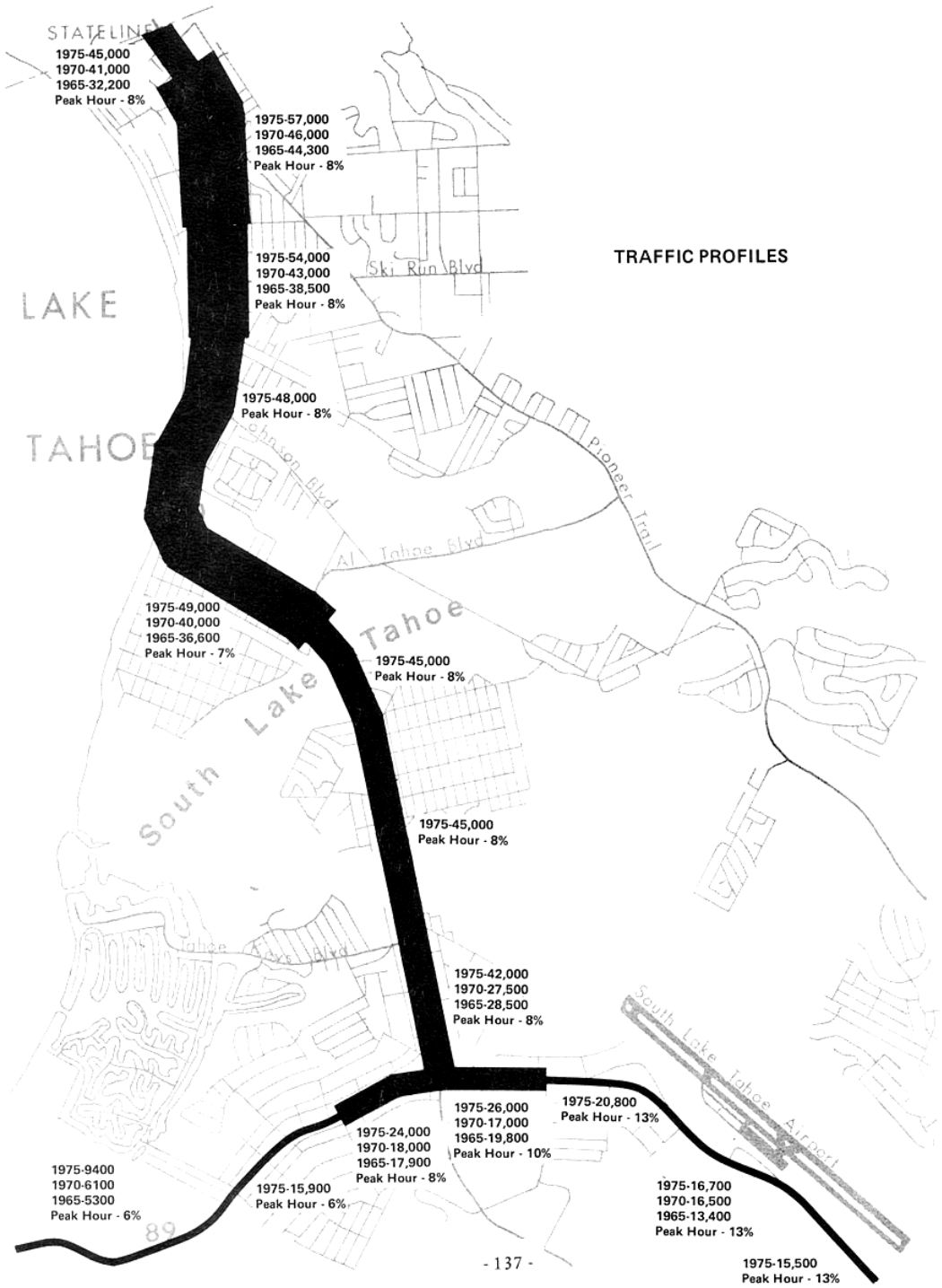

Figure 3-14—Traffic volume at South Lake Tahoe, from 1976 CTRPA Regional Transportation Plan.

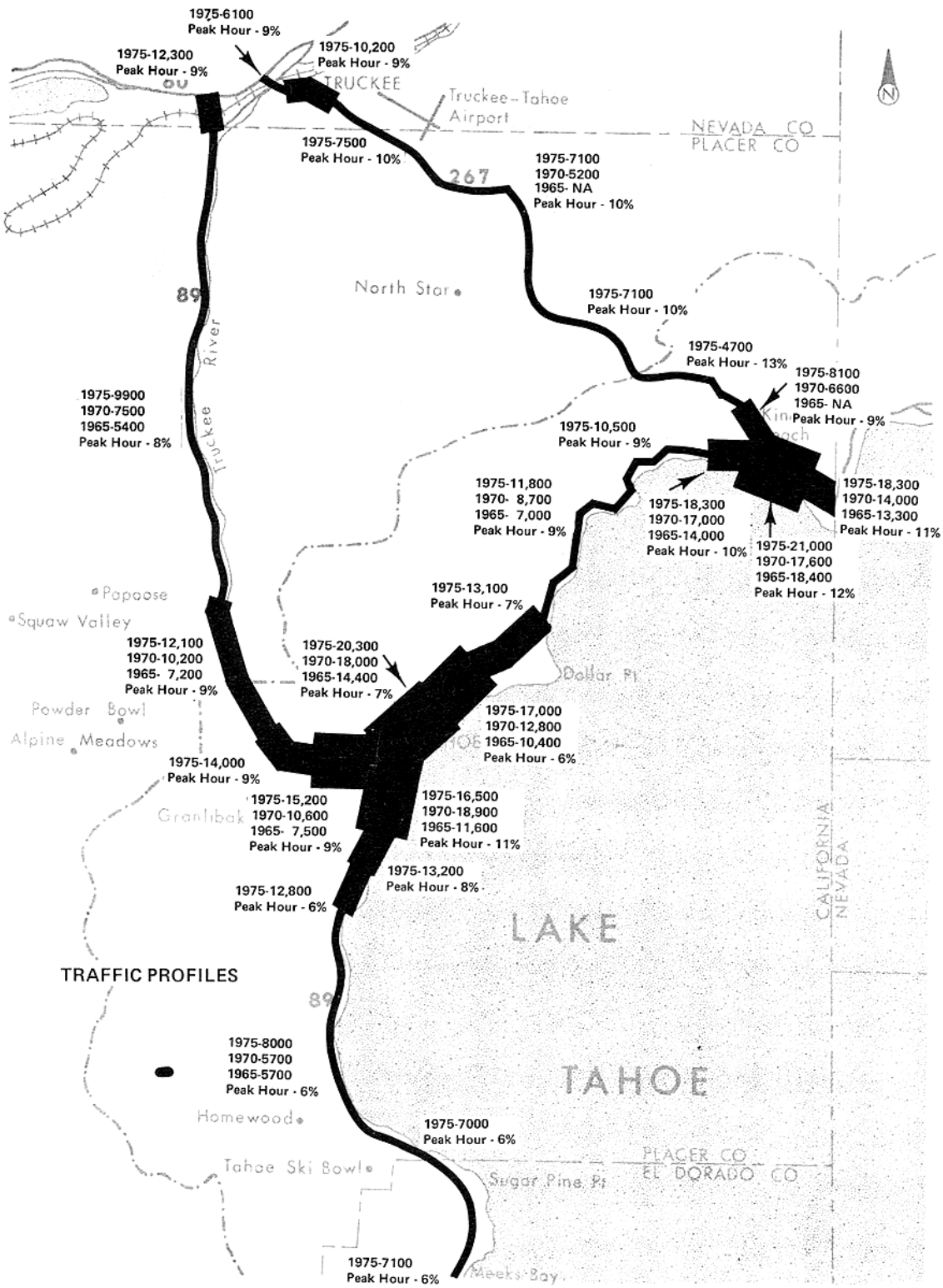

Figure 3-15—Traffic volume at the north and west shores of Lake Tahoe, from the 1976 CTRPA Regional Transportation Plan.

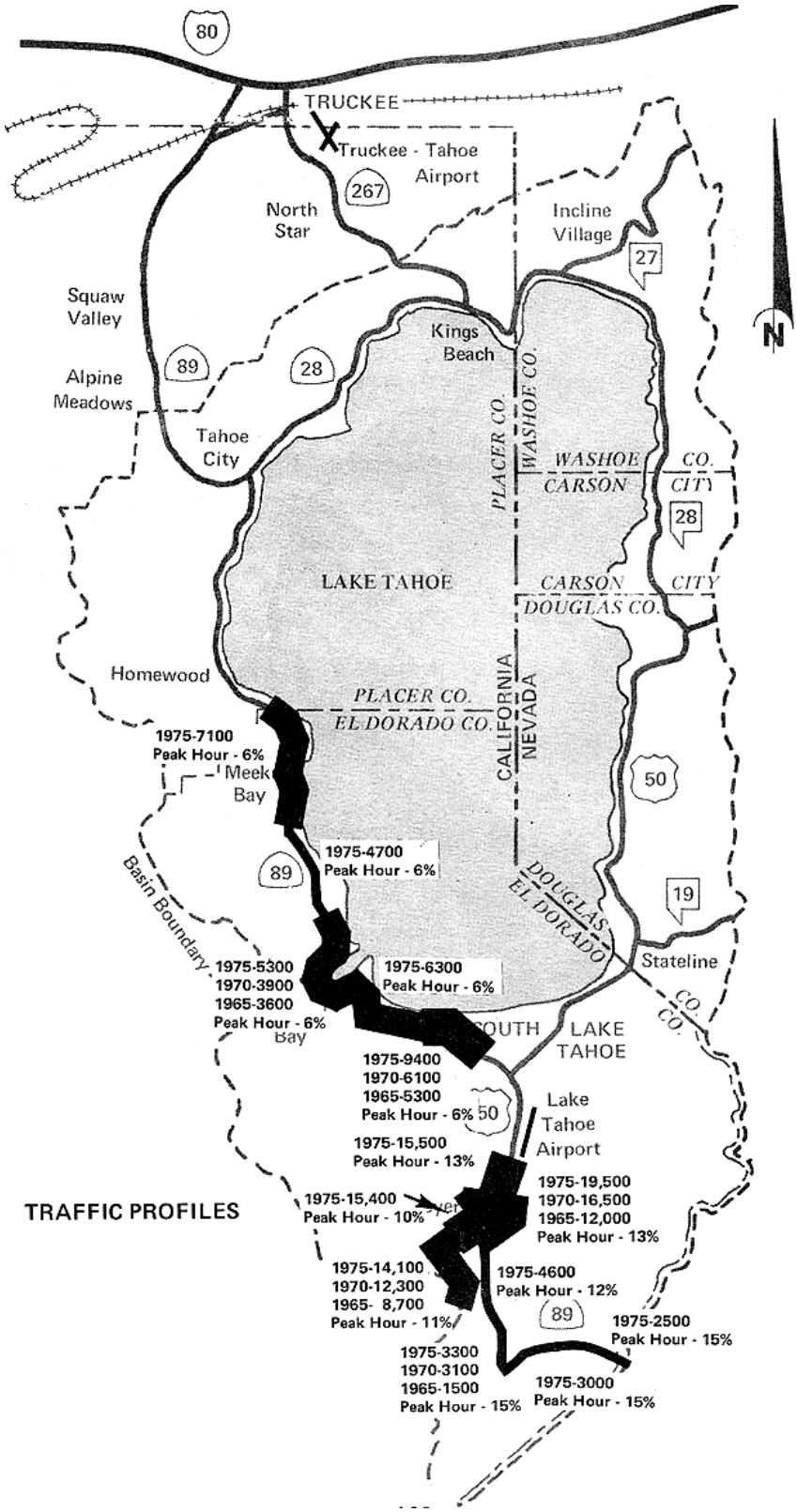

Figure 3-16—Traffic volume on highways 89 and 50 on the west and south shores of Lake Tahoe, from the 1976 CTRPA Regional Transportation Plan.

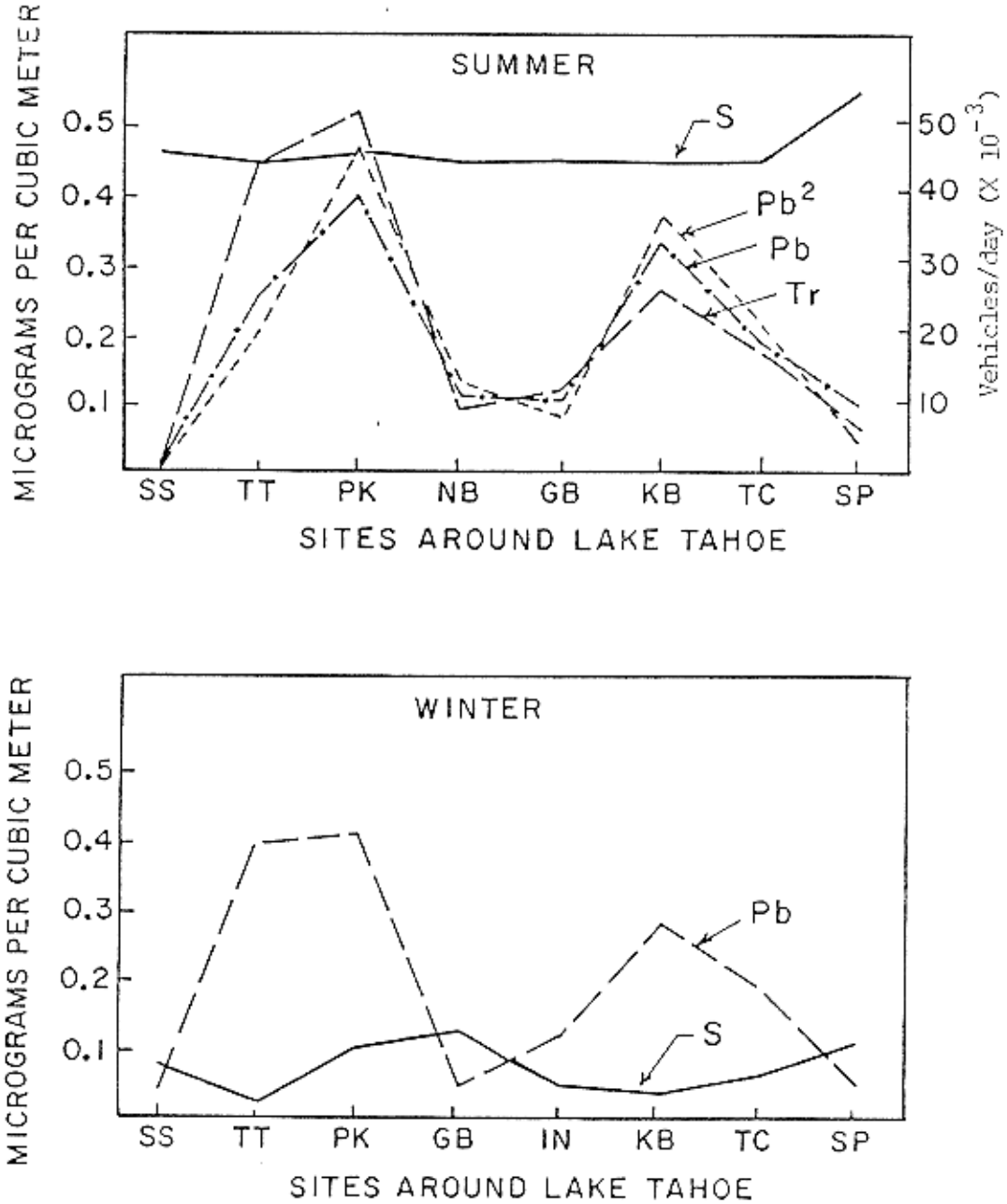

Figure 3-17—Concentration of lead and sulfur, correlated with traffic volume at sites around Lake Tahoe for summer and winter, from the 1979 ARB/UC Davis Air Quality study.

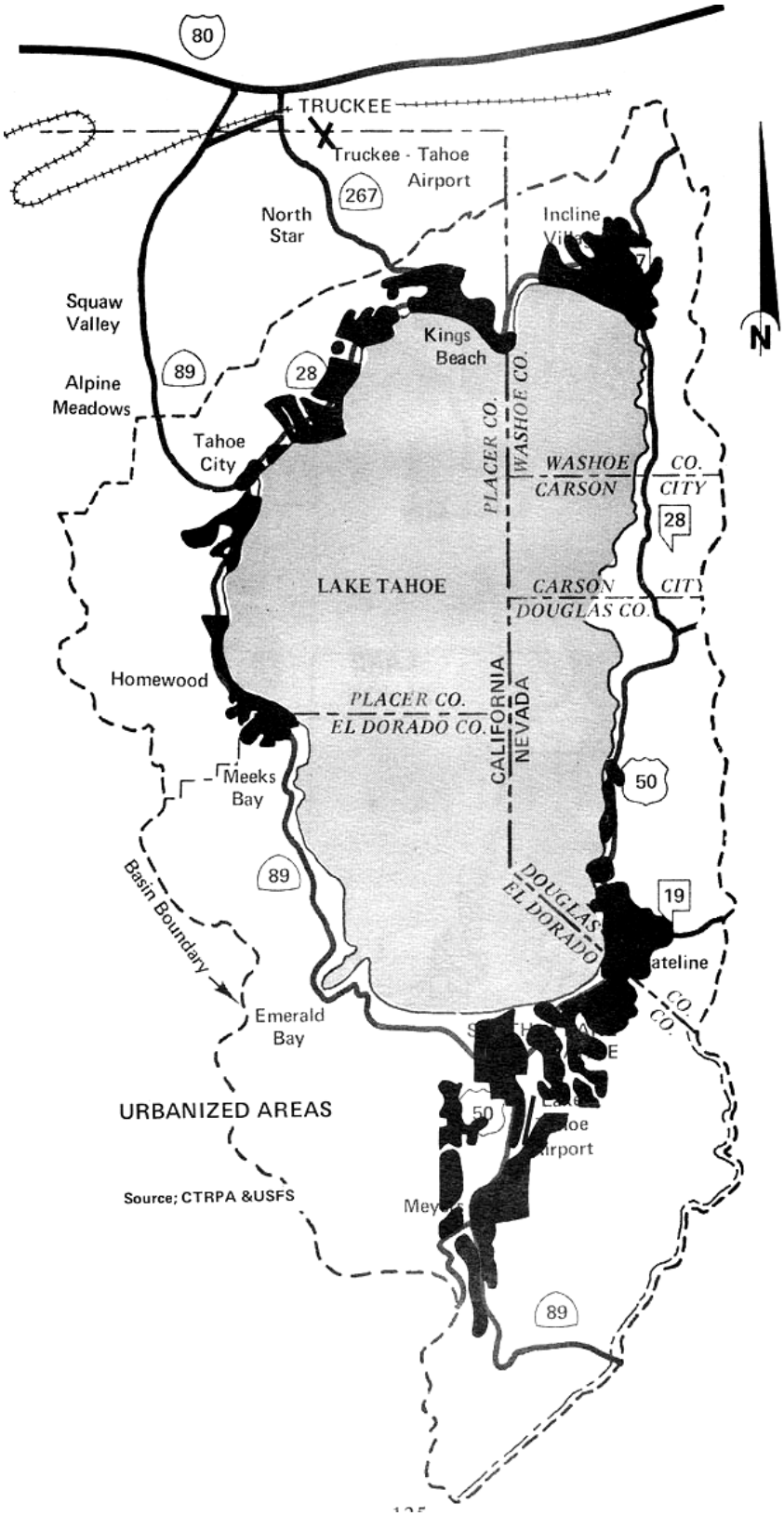

Figure 3-18—CTRPA map of urbanized areas, from 1976 Regional Transportation Plan.

Lake Tahoe Airshed Model (LTAM) for NO_x

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DELTA Group, University of California, Davis

Values used in equations (User Input Variables)

Between Cell transfer rate (over water)	0.94	94	% Goes into the next cell
Between Cell transfer rate (over forest)	0.94	94	% Goes into the next cell
Long range transport (from out of basin)	0	$\mu g/m^3$	

Road NO_x	Manual Input	$\mu g/m^3$
Interstate 80	100.0	$\mu g/m^3$
Highway 267 from Truckee to KB	14	$\mu g/m^3$
Highway 89 from Truckee to Squaw	20	$\mu g/m^3$
Highway 89 from Squaw to Tahoe City	24	$\mu g/m^3$
Tahoe City Local	40	$\mu g/m^3$
Highway 28 from TC to Kings Beach	26	$\mu g/m^3$
Highway 28 Kings Beach to Incline	36	$\mu g/m^3$
Incline Local	42	$\mu g/m^3$
Highway 431 over Mt. Rose	6	$\mu g/m^3$
Highway 28 from Incline to 50	7	$\mu g/m^3$
Highway 50 over Spooner	24	$\mu g/m^3$
Highway 50 Glenbrook to Stateline	24	$\mu g/m^3$
Highway 207 Kingsbury Grade	6	$\mu g/m^3$
Stateline South Lake Tahoe	84	$\mu g/m^3$
Pioneer Trail	10	$\mu g/m^3$
Highway 50 Echo Summit to Meyers	28	$\mu g/m^3$
Highway 50 Meyers to the "Y"	30	$\mu g/m^3$
Highway 89 from "Y" to Camp Richardson	18	$\mu g/m^3$
Highway 89 from CR to Meeks Bay	12	$\mu g/m^3$
Highway 89 from Meeks Bay to TC	50	$\mu g/m^3$
Highway 89 over Luther Pass	10	$\mu g/m^3$
Kings Beach Local	42	$\mu g/m^3$
Meyers Local	30	$\mu g/m^3$
Urban NO_x emission	15	$\mu g/m^3$

Lake cell equation (type B with variable wind) for Summer Day

proportion north-west wind =	0.1	10	% N-W Wind
proportion west wind =	0.3	30	% W Wind
proportion south-west wind =	0.6	60	% S-W Wind
These must sum to one!	1		

Lake cell equation (type C with variable wind) for Summer Day

proportion north-west wind =	0.6	60	% N-W Wind
proportion west wind =	0.3	30	% W Wind
proportion south-west wind =	0.1	10	% S-W Wind
These must sum to one!	1		

Lake cell equation (type B with variable wind) for Summer Night

proportion north-west wind =	0.3333	33.33	% N-W Wind
proportion west wind =	0.3333	33.33	% W Wind
proportion south-west wind =	0.3333	33.33	% S-W Wind
These must sum to one!	0.9999		

Lake cell equation (type C with variable wind) for Summer Night

proportion north-west wind =	0.3333	33.33	% N-W Wind
proportion west wind =	0.3333	33.33	% W Wind
proportion south-west wind =	0.3333	33.33	% S-W Wind
These must sum to one!	0.9999		

Lake cell equation (type B with variable wind) for Winter

proportion north-west wind =	0.3333	33.33	% N-W Wind
proportion west wind =	0.3333	33.33	% W Wind
proportion south-west wind =	0.3333	33.33	% S-W Wind
These must sum to one!	0.9999		

Lake cell equation (type C with variable wind) for Winter

proportion north-west wind =	0.3333	33.33	% N-W Wind
proportion west wind =	0.3333	33.33	% W Wind
proportion south-west wind =	0.3333	33.33	% S-W Wind
These must sum to one!	0.9999		

Figure 3-19a—Input page for roadway NO_x and wind parameters in the LTAM.

80	80	0	ruck	80	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	431
0	0	80	80	0	ruck	267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	431	0
0	0	0	89	0	0	0	267	267	267	0	0	0	0	0	0	0	0	0	0	0	0	431	0	0
0	0	0	89	0	0	0	0	0	0	267	0	0	0	0	0	0	0	0	0	0	431	0	0	0
0	0	0	89	0	0	0	0	0	0	267	0	0	0	0	0	0	0	0	0	0	431	0	0	0
0	0	0	89	0	0	0	0	0	0	0	267	0	0	0	0	0	0	0	0	0	431	0	0	0
0	0	0	89	0	0	0	0	0	0	0	0	w/r	0	0	0	0	0	0	0	0	431	0	0	0
0	0	0	89	0	0	0	0	0	0	0	0	0	r	0	0	0	0	0	431	431	nclin	u	0	0
0	0	0	89	0	0	0	0	0	0	0	0	0	s/r	s/r	s/r	0	s/r	s/r	s/r	s/r	s/r	28	0	0
0	0	0	89	0	0	0	0	0	0	0	0	0	s/r	0	0	s/r	0	0	0	0	0	s/r	0	0
0	0	0	89	0	0	0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	89	0	0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	89	0	0	0	0	0	s/r	28	s	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	89	0	0	0	0	s/r	0	s	0	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	89	0	0	TC	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	0	89	89	TC	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	s/r	0	0
0	0	0	0	0	750	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	s	28	0	0
0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	s	28	0	0
0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	s	0	28	0	0
0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	s	0	0	28	0	50
0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	s	0	50	w/r	0
0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	s	u	50	0	0
0	0	0	0	0	0	0	s/r	s/r	s/r	0	0	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	0	s/r	0	0	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	s	50	0	0	0	0
0	0	0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	0	s/r	0	0	0	0
0	0	0	0	0	0	0	0	0	0	89	s	0	0	0	0	0	0	0	0	0	s	50	0	207	w/r
0	0	0	0	0	0	0	0	0	0	89	89	s	s	0	0	0	0	0	0	0	s	r/u	207	0	0
0	0	0	0	0	0	0	0	0	89	b	b	s	s	0	0	0	0	0	0	s	r/u	u	0	0	0
0	0	0	0	0	0	0	0	0	0	89	89	89	s	s	0	0	0	s/r	s/r	r/u	u	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	89	89	89	s/r	s	s	u	r/u	SLT	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	89	u	r/u	SLT	SLT	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	r/u	0	0	r	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	r	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	r	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	r	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	r/u	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	ayer	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	w/r	89	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	50	50	50	w/r	89	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	50	50	50	50	0	0	0	0	0	89	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	89	0	0	0	0	0	0	0	0

Figure 3-19b—Input map for the LTAM. Note input of source is possible for any forest (green) or lake (blue) square. Each square represents 2.56 square kilometers in the LTAM. Road inputs are entered on a separate sheet.

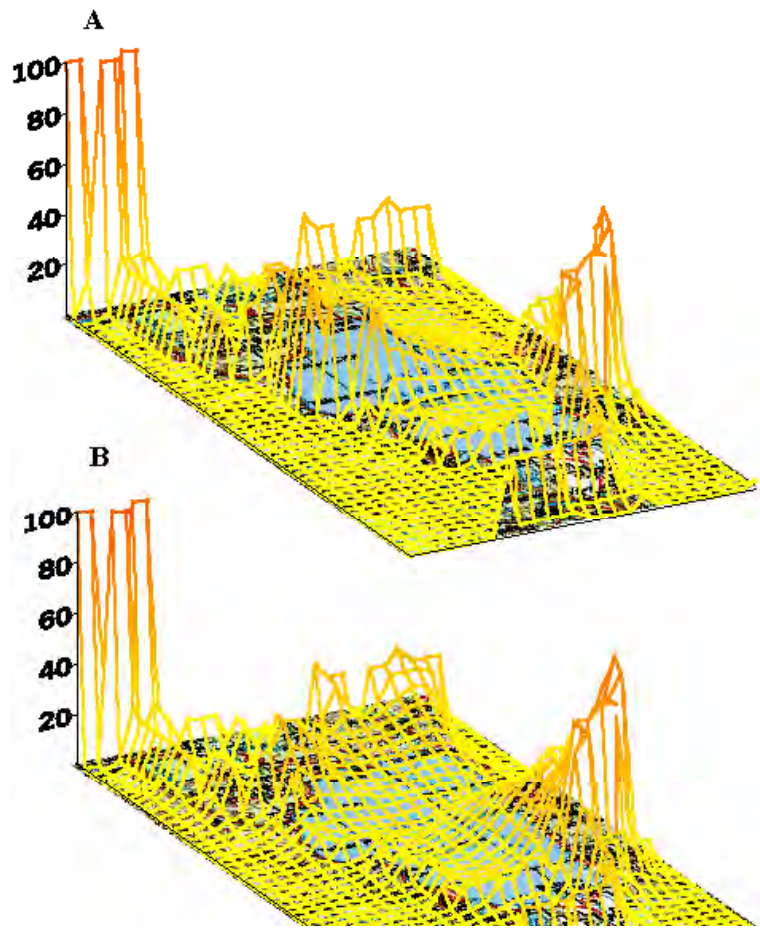


Figure 3-20—LTAM output for NO_x for average summer day (top) and summer night (bottom) 12-hour period. The baseline is set a 0 $\mu g/m^3$ and is at a maximum at 100 $\mu g/m^3$. Note that during the day the LTAM predicts significant transport of NO_x from the Highway 89 corridor extending southeast from Tahoe City. Although Tahoe City is not a large urban center, the addition of pollutants from I-80 and Highway 89 is predicted to be highly important for pollutant interaction with the Lake Tahoe surface. The output for summer night stagnation from the LTAM predicts that pollutants stay in close contact with the lake during this period.

- Human health and regulatory impacts:
  - Carbon monoxide, gas
  - $PM_{2.5}$ particles, fine particles
  - PM_{10} particles, intermediate sized particles
  - Ozone, gas
- Forest health:
  - Ozone, gas

Then for each of these impacts, model analysis can be accomplished for three conditions that dominate the weather in the Lake Tahoe basin-- summer day summer night winter and spring for some parameters.

Currently, efforts are focused on nitrogenous pollutants (NO, NO_2, NO_x, ammonium nitrate, nitric acid, and nitrogenous organic material) phosphate (TSP, PM_{10}, and $PM_{2.5}$ particles) and fine soils because of their importance in lake eutrophication and atmospheric visibility concerns. Gaseous pollutants, such as ozone (O_3) and carbon monoxide (CO), which are important for forest and human health, can be modeled using the general gas model portion of the LTAM for all three

meteorological regimes. For atmospheric inputs to lake clarity, knowledge of the concentration is not adequate by itself and needs what fraction actually enters the water by either direct (surface deposition) or indirect means. This deposition and uptake by the lake should be the subject of future research in the Lake Tahoe basin.

Derivation of Model Parameters

Within the Lake Tahoe basin a number of particulate and gaseous pollutants are important for lake clarity, forest health, and human health. The ability of the LTAM to predict concentration of these species throughout the basin lies in the quality of data input into the model. Invariable pollutant parameters included in the model are derived from the aforementioned studies (CARB 1974; CARB/UCD 1979). The derivation of the model parameters is broken down into pollutant type by specific concern. In this effort, a comprehensive representation of each pollutant responsible for each individual ecosystem concern prioritized above is given.

In Table 3-2 and the summaries that follow, actual measured values are in bold-face type, certain to $\pm$ 15%. All parameters in normal type are predictions based on theory, extrapolations, or estimates, with a nominal uncertainty of $\pm$ 30%. Parameters in italics are even more uncertain, varying by up to a factor of 2 in either direction, while estimates, some of the crudest sort, are in italics plus a question mark. Parameters listed include: C_{uw}, which is the upwind concentration in micrograms per cubic meter ($\mu g/m^3$), S (local), which is the local source of the pollutant, D_w, which is the dispersion of pollutant per km over water, D_f, which is the dispersion of pollutant over forest, v_d, which is the velocity of deposition, and finally a parameter that is the ratio of efficiency for haze or retention in the lake, or the human health-based standard.

Pollutants Tied to Lake Clarity

Nitrogen oxides (NO_x)—Upwind out-of-basin NO_x sources are set to zero (Figure 3-19). Although there is likely some input of NO_x from the Highway 50 and Highway 80 corridors, data supporting this hypothesis do not exist. With the new Echo Summit CARB site, there will soon be data on this source. For local roadway NO_x, we use the results of a comparison of traffic and NO_x concentration at sites around the basin (Figure 3-21), where 50,000 vehicles/day equals a concentration in major roadway cells of 120 $\mu g/m^3$. We then can include a technological improvement factor based on Highway 50 traffic increases over the period from 1980 to 1994 (x%) and the observed decrease of pollutants at the South Lake Tahoe CARB site (y%). Using +15% for x and - 20% for y, we can arrive at a value of 44% lower than the estimated source from Figure 3-21, or 84 $\mu g/m^3$ NO_x per 50,000 vehicles/day. This new value then is coded into each of the 23 model road segments (r) and scaled proportional to traffic volume within the typical estimates from the 1976 CTRPA traffic study. Traffic on any segment can be modified to observe the change in NO_x concentration, which then is propagated downwind. Note that the CARB 1973 measurements were not always close to the largest road; while some were almost next to the road (King's Beach, for example), others were quite far removed (Tahoe Keys, Nevada Beach). On the average, sites were within half a km of the road. Thus, some urban sources also were included in the measurement.

For the cells coded "urban" (u) but lacking a major road, we used an estimate of traffic density based on a few measurements (CARB 1979-1994) and the California emission fraction of roadway to nonroadway NO_x sources. However, because the area lacks heavy industry, this ratio had to be lowered, while heavier local space heating, even in summer but especially in winter, raises the ratio. Urban cells are coded with a fixed value of 21 $\mu g/m^3$. These sources then are added to all cells marked with highway number, city name, r, r/u, and u in the LTAM input page.

Nitrogenous particles—The source of nitrate particles (NO_3) is largely upwind transport in the

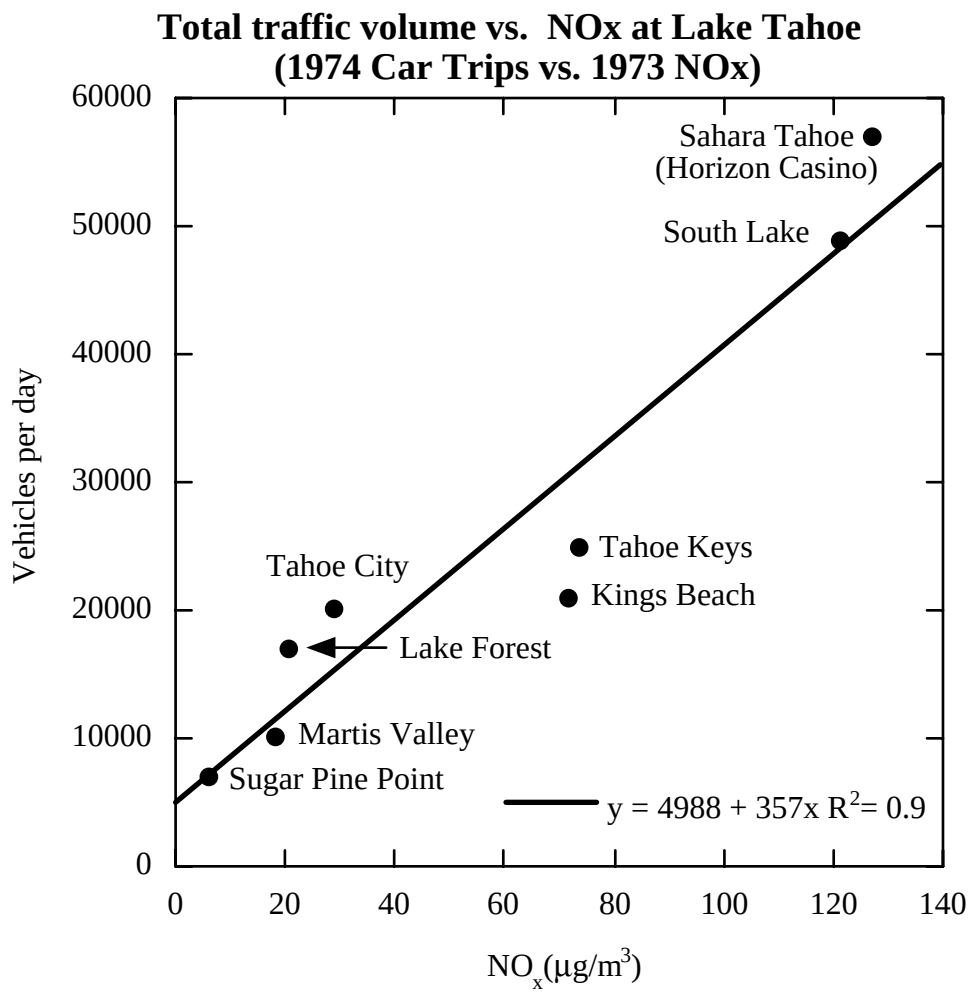


Figure 3-21—Correlation between traffic volume and NO_x concentration in the Lake Tahoe basin. The traffic data is from the 1974 CalTrans study, and the NO_x data is from the 1973 ARB study. Note that at 5,000 cars (the y-intercept) NO_x is seen as negligible for purposes of the LTAM.

summer, labeled t, and from local sources in the winter (Figure 3-11). The winter nitrate values correlate weakly with both NO_x (automotive) and wood smoke (urban). Ammonium (NH_4) is derived from ammonium sulfate and ammonium nitrate and thus also shares the same summer-winter dichotomy. While there is no transport into the basin at night, the long residence time predicts that the basin is uniformly filled with fine nitrate particles each summer night left over from the previous day. Published nitrate values are 24-hour averages.

Organic nitrogen arises almost entirely from such biological sources as pollen and from such biodebris as pine needles. The small amount of data on this potentially large source is weak. The LTAM uses values that are based on summer pollen measurements, using CARB 1973 data from TSP samplers with a roughly 30 micrometer diameter intake restriction. The potential nitrate component of the biodebris then is estimated and set as a default (i.e., no variable input to the model).

Phosphorous—Phosphorus is found only in nanogram amounts in $PM_{2.5}$ particles, but significant levels were seen in a limited number of samples collected in 1970s before strict adherence to PM_{10} and $PM_{2.5}$ collection was implemented. Thus, we

assume that most phosphorus occurs in particles above 10 micrometers in diameter but less than 30 micrometers aerodynamic diameter. This latter point is important because particles that occur in flakes, such as many types of ash, may be much larger than 30 microns in lateral dimensions but settle slowly to the surface and thus may transport more efficiently than expected based only on particle size. Although only limited data on phosphorous concentration of super-PM_{10} particles exist, deposition studies by the Tahoe Research Group at the University of California at Davis indicate a significant atmospheric contribution of this important nutrient (Jassby 1994).

Fine soil particles—Local fine soils have a roughly equal local and transported component, set at 1/2 in the model (Figure 3-11). Transported sources are in spring, summer, and fall and are assumed to be uniform across the basin. The local source of fine particles is largely from roadways, and particles are usually about 10 microns in size. This can be seen from the ratio of TSP to PM_{10}, which is typically 0.5. These soils also have a phosphorus component, but the amounts are low and the availability for biological activity is unknown.

NO_x

	C_{uw}	S (local)	D_w	D_f	v_d	Retention in lake
Summer day	0.08	r, u	0.9/km	**0.4/km**	2 cm/s	0.1
Summer night	0.07	r, u	0.9/km	0.4/km	2 cm/s	0.1
Winter	0.04	r, u	0.9/km	0.15/km	2 cm/s	0.1

NO_3:

	C_{uw}	S (local)	D_w	D_f	v_d	Retention in lake
Summer day	**0.4**	t, u	1.0/km	1.0/km	0.03 cm/s	1.0
Summer night	**0.4***	t, u	1.0/km	1.0/km	0.03 cm/s	1.0
Winter	0	r, u	0.8/km	0.15/km	0.03 cm/s	1.0

NH_4:

	C_{uw}	S (local)	D_w	D_f	v_d	Retention in lake
Summer day	**0.4**	t, u	1.0/km	1.0/km	0.03 cm/s	1.0
Summer night	**0.4***	t, u	1.0/km	0.6/km	0.03 cm/s	1.0
Winter	0	r, u	0.15/km	0.3/km	0.3 cm/s	1.0

Organic Nitrogen:

	C_{uw}	S (local)	D_w	D_f	v_d	Retention in lake
Summer day	*1.5*	f	0.4/km	0.150/km	2 cm/s	1.0
Summer night	*1.5*	f	0.15/km	0.05/km	2 cm/s	1.0
Winter	?	?	0.15/km	0.05/km	2 cm/s	1.0

Phosphorus:

	C_{uw}	S (local)	D_w	D_f	v_d	Retention in lake
Summer day	?	u, f	0.4/km	0.15/km	2 cm/s	1.0
Summer night	?	u, f	0.15/km	0.05/km	2 cm/s	1.0
Winter	?	u	0.15/km	0.05/km	2 cm/s	1.0

Fine soil particles:

	C_{uw}	S (local)	D_w	D_f	v_d	Retention in lake
Summer day	1.4	t, r	0.4/km	0.15/km	2 cm/s	1.0
Summer night	1.4	t, r	0.15/km	0.05/km	2 cm/s	1.0
Winter	1.1	r	0.15/km	0.05/km	2 cm/s	1.0

Pollutants Tied to Atmospheric Visibility

Visibility in the Lake Tahoe basin is probably the best understood of the major air quality impacts, largely due to the successful TRPA effort to measure and analyze visibility as part of the basin carrying capacity exercise that began in the late 1980s. These capacities were evaluated for both regional (basin-wide) and subregional (South Lake Tahoe) scales and are summarized in Molenar et al. (1994). The relative importance of each parameter is given in Table 3-3.

Organic compounds—Organic matter in the atmosphere over Lake Tahoe is overwhelmingly derived from wood smoke from upwind, urban, or forest sources. There is a contribution, however, from vehicles that can become important in winter in heavily traveled corridors. In this component, visibly smoking vehicles, including older cars and diesel cars, trucks, and buses, dominate the source.

Nitrogenous particles—The sources and implications of nitrogenous particles are described above; here, we include only the visibility component.

Sulfate particles—Sulfate particles are overwhelmingly derived from upwind transport in both winter and summer (Figure 3-11). Thus, they are assumed to be uniform across the basin for the purposes of the model.

Fine soil particles—The implications and sources of fine soil particles are described above; included here is only the visibility portion.

NO_3:

	C_{uw}	S (local)	D_w	D_f	v_d	Efficiency for haze
Summer day	**0.4**	t, u	1.0/km	1.0/km	0.03 cm/s	1
Summer night	**0.4**	t, u	1.0/km	1.0/km	0.03 cm/s	1
Winter	0	u, r	0.8/km	0.15/km	0.03 cm/s	1

NH_4:

	C_{uw}	S (local)	D_w	D_f	v_d	Efficiency for haze
Summer day	**0.4**	t, u	1.0/km	1.0/km	0.03 cm/s	1
Summer night	**0.4**	t, u	1.0/km	0.6/km	0.03 cm/s	1
Winter	0	u, r	0.15/km	0.3/km	0.03 cm/s	1

Sulfate particles:

	C_{uw}	S (local)	D_w	D_f	v_d	Efficiency for haze
Summer day	**0.4**	t	1.0/km	1.0/km	0.03 cm/s	1
Summer night	**0.4**	t	1.0/km	1.0/km	0.03 cm/s	1
Winter	01	u, r	0.8/km	0.15/km	0.03 cm/s	1

Fine soil particles:

	C_{uw}	S (local)	D_w	D_f	v_d	Efficiency for haze
Summer day	**0.6**	t, r	0.4/km	0.15/km	2 cm/s	0.3
Summer night	**0.6**	t, r	0.15/km	0.05/km	2 cm/s	0.3
Winter	**0.1**	r	0.15/km	0.05/km	2 cm/s	0.3

Table 3-3—Contribution of fine aerosol components to visibility at Lake Tahoe.

Regional Reconstructed Scattering, Absorption, and Extinction (Mm^{-1}) Bliss State Park, Fall 1990 to Summer 1992					
Aerosol b_{scat}	**Spring**	**Summer**	**Fall**	**Winter**	**Yearly**
Sulfates	3.4	4.7	3.0	1.3	3.0
Nitrates	1.7	1.3	1.3	1.3	1.4
Organic Carbon (OC)	2.3	4.2	5.2	2.9	3.6
Light Absorbing Carbon (LAC)	0.5	0.6	0.6	0.3	0.5
Fine Soil	0.9	0.6	0.4	0.3	0.6
Course Mass	2.3	2.6	2.3	2.0	2.3
Total b_{scat}	11.1	14.0	12.8	8.1	11.4
b_{abs}	5.0	7.4	7.8	4.4	6.2
Rayleigh b_{scat}	10.0	10.0	10.0	10.0	10.0
Total b_{scat}	26.1	31.4	30.6	22.5	27.6
Visual Range (km)	150	125	130	175	140

Subregional Reconstructed Scattering, Absorption, and Extinction (Mm-1) South Lake Tahoe, Spring 1989 to Summer 1992					
Aerosol b_{scat}	**Spring**	**Summer**	**Fall**	**Winter**	**Yearly**
Sulfates	4.3	6.0	3.8	2.1	4.3
Nitrates	2.1	1.7	2.1	4.3	2.6
Organic Carbon (OC)	8.8	7.5	11.4	22.4	12.7
Light Absorbing Carbon (LAC)	1.7	1.5	2.1	3.2	2.1
Fine Soil	1.9	1.4	1.1	1.3	1.4
Course Mass	7.1	8.1	7.3	13.0	8.9
Total b_{scat}	25.9	26.2	27.8	46.3	32.0
b_{abs}	22.4	20.7	28.2	42.8	28.5
Rayleigh b_{scat}	10.0	10.0	10.0	10.0	10.0
Total b_{ext}	58.3	56.9	66.0	99.1	70.5
Visual Range (km)	65	70	60	40	55

Source: Molenar et al. 1994

Pollutants Tied to Forest Health

The primary air pollution impact on the Sierran forest is ozone (Cahill 1996). The key parameter that best matches the decline of the most important sensitive species, Jefferey pine, is ozone dose (concentration multiplied by time) above 0.09 ppm. This level of pollutant is rarely seen at Lake Tahoe, and surveys of ozone damage (Pedersen 1989) show only marginal signs of impact. However, unlike almost any other California location, ozone levels slowly continue to climb at Lake Tahoe and are approaching the point where damage probably will occur in the future. This O_3 increase is most likely due to the rapid development of the foothill communities east of Sacramento and Stockton.

Air Pollutants with Health and Regulatory Issues

Carbon monoxide gas—Carbon monoxide (CO) is a human health pollutant that is derived primarily from combustion. A secondary, and more minor, source of CO is from oxidation of methane and nonmethane hydrocarbons in the formation of ozone. At Lake Tahoe the CO measured at most sites is locally generated. Currently, CO is not a

major concern in the Lake Tahoe basin, as advances in combustion technology have largely curbed this source. In fact, CARB data indicate a leveling off or decline of CO at most measured sites in the basin.

Fine and intermediate sized atmospheric particles—Fine or $PM_{2.5}$ particles have sizes that usually are dominated by particles around 0.5 micrometers in diameter. The settling velocities of such particles are extremely small but are readily incorporated into fog and rain, and are removed by wet deposition. Roughly half the measured concentration each summer is from upwind sources and half is from local sources, while in winter the sources are more than 80 percent local. The mixture of particles at South Lake Tahoe and Bliss State Park as a function of season is shown in Figure 3-22 and Table 3-4. The new US EPA federal standards are 65 $\mu g/m^3$, 24-hr, and 15 $\mu g/m^3$, annual average, although these standards are under review by the courts and the EPA (see Issue 3 regarding air quality standards).

PM_{10} or intermediate sized particles include some transported particles in summer, because PM_{10} includes $PM_{2.5}$ particles, with roughly half transported, half local. In winter, they are again largely local in origin. The mix of particles at South Lake Tahoe and Bliss State Park as a function of season is shown in Figure 3-22. A few violations of the 24-hr California standard have occurred.

Tropospheric ozone—Ozone (O_3) at Lake Tahoe is low to moderate during most of the

O_3:

	C_{uw}	S (local)	D_w	D_f	v_d	CA Standard for Tahoe
Summer day	0.08	t	1.0/km	1.0/km	2 cm/s	0.09 ppm
Summer night	0.07	t	1.0/km	1.0/km	2 cm/s	0.09 ppm
Winter	0.04	t	1.0/km	1.0/km	2 cm/s	0.09 ppm

Carbon monoxide:

	C_{uw}	S (local)	D_w	D_f	v_d	CA Standard for Tahoe
Summer day	0	r	0.9/km	**0.3/km**	2 cm/s	0.06 ppm
Summer night	0	r	0.9/km	0.3/km	2 cm/s	0.06 ppm
Winter	0	r	0.9/km	0.3/km	2 cm/s	0.06 ppm

$PM_{2.5}$:

	C_{uw}	S (local)	D_w	D_f	v_d	EPA Standard
Summer day	4	u, f, r	0.6/km	0.8/km	0.03 cm/s	65 $\mu g/m^3$
Summer night	4	u, f, r	0.3/km	0.6/km	0.03 cm/s	65 $\mu g/m^3$
Winter	2	u, f, r	0.15/km	0.3/km	0.03 cm/s	65 $\mu g/m^3$

PM_{10}:

	C_{uw}	S (local)	D_w	D_f	v_d	CA Standard
Summer day	7	u, f, r	0.4/km	0.15/km	2 cm/s	50 $\mu g/m^3$
Summer night	7	u, f, r	0.15/km	0.05/km	2 cm/s	50 $\mu g/m^3$
Winter	3	u, r	0.15/km	0.05/km	2 cm/s	50 $\mu g/m^3$

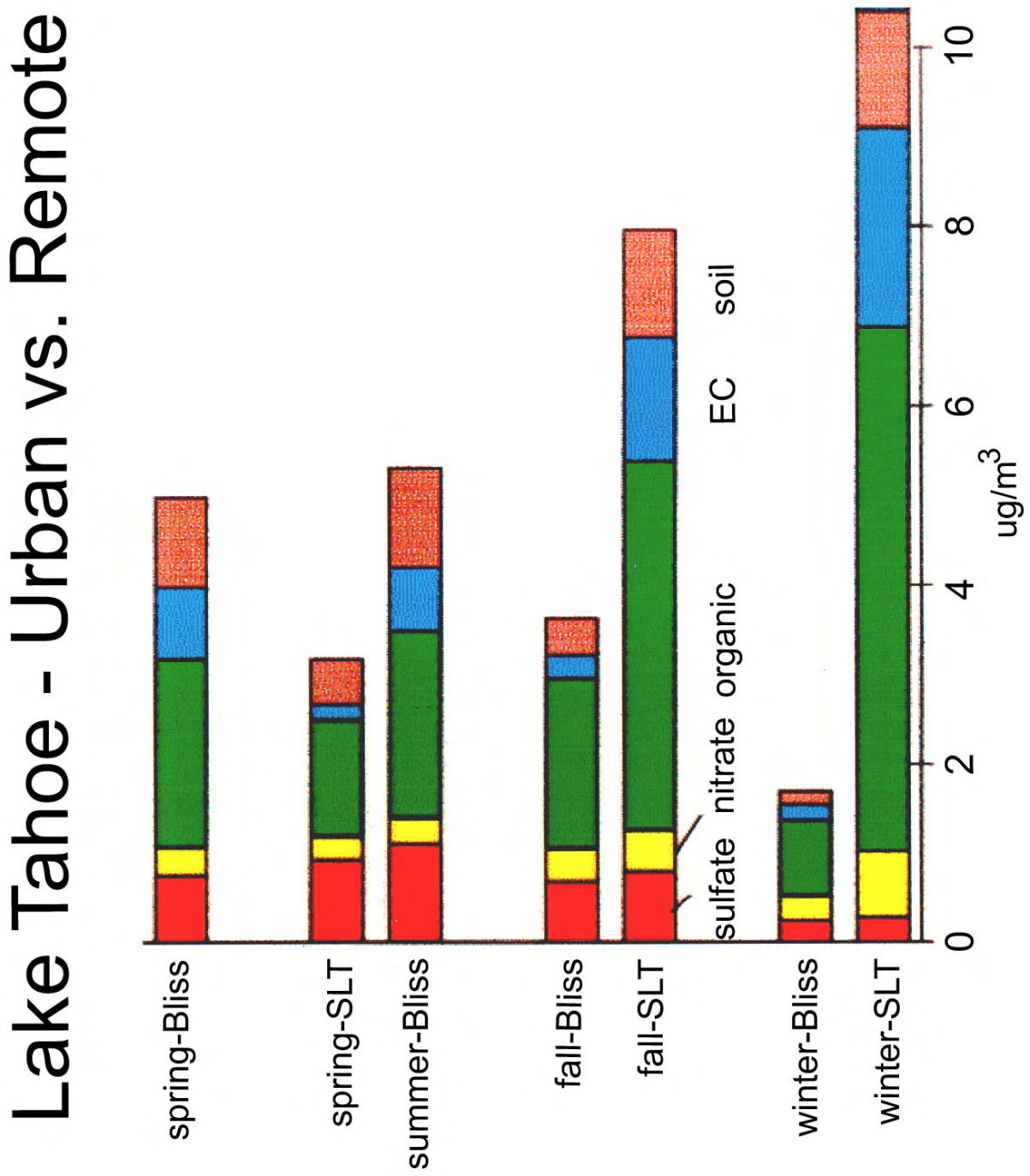


Figure 3-22—Comparison of aerosol components at South Lake Tahoe and D. L. Bliss State Park for both the winter and summer periods.

Table 3-4—Components of fine mass at Lake Tahoe and other Sierran/Cascadian sites.

Comparison of Sierra-Cascade Aerosol Concentrations from 1992 to 1993 High Elevation Sites

Major Constituents	(Micrograms/m³)						
	Sequoia NP	Yosemite NP	Bliss SP	**South Lake Tahoe**	Lassen NP	Crater Lake NP	**Washington DC**
Coarse Mass	(x.09)						
PM_{10}	N.A.	11.00	5.85	**18.20**	7.05	6.21	**23.10**
Fine Mass							
$PM_{2.5}$	8.49	5.04	3.39	**9.65**	3.05	2.87	**19.70**
Estimated Sum	6.86	4.17	2.90	**9.21**	2.55	2.41	**18.50**
Organics	2.94	1.84	1.16	**5.52**	1.18	0.98	**5.12**
Sulfates	2.14	1.19	0.84	**1.03**	0.65	0.62	**9.54**
Nitrates	1.58	0.48	0.29	**0.53**	0.11	0.14	**2.41**
Soil	0.73	0.52	0.44	**0.88**	0.03	0.39	**1.03**
Smoke Tracers							
b(abs) (10-8m-1)	13.50	7.83	5.66	**29.30**	4.99	5.25	**41.80**
Estimated Mass (micrograms/m³)	0.14	0.08	0.06	**0.29**	0.04	0.05	**0.42**
KNON (ng/m³)	37.89	23.80	14.80	**41.60**	12.40	6.58	**16.40**
Trace Elements	(Nanograms/m³)						
Nickel	0.19	0.09	0.07	**0.13**	0.07	0.08	**3.53**
Copper	1.58	0.47	0.44	**1.41**	2.53	0.84	**4.76**
Zinc	3.12	1.55	1.29	**5.13**	1.52	3.33	**18.60**
Selenium	0.28	0.19	0.12	**0.12**	0.09	0.06	**2.08**
Bromine	2.65	1.56	1.16	**1.63**	0.91	0.75	**5.12**
Lead	1.29	0.78	0.68	**1.71**	0.53	0.96	**6.99**

Notes:
Sequoia x 0.9 entry corrects to Giant Forest elevation, 6,000 feet.
Sites in bold – urbanized.
Ni, As, and Se often below detectable limit.
NP = National Park.
SP = State Park.

year, with few violations of the state (0.09 ppm hr) standard and no violations of the state 8-hour or the federal 1-hour (0.12 ppm) standards. However, unlike almost any other California city, ozone levels continue to slowly climb in South Lake Tahoe and are approaching the point where violations probably will occur (Figure 3-23). This is likely due to transport of O_3 precursors emitted in the rapidly developing foothill communities east of Sacramento and Stockton.

Preliminary Validation of the LTAM

In order to determine the validity of the predictions derived from the LTAM it is necessary to perform some simple field experiments. For example, $PM_{2.5}$ sampling during a prescribed fire of

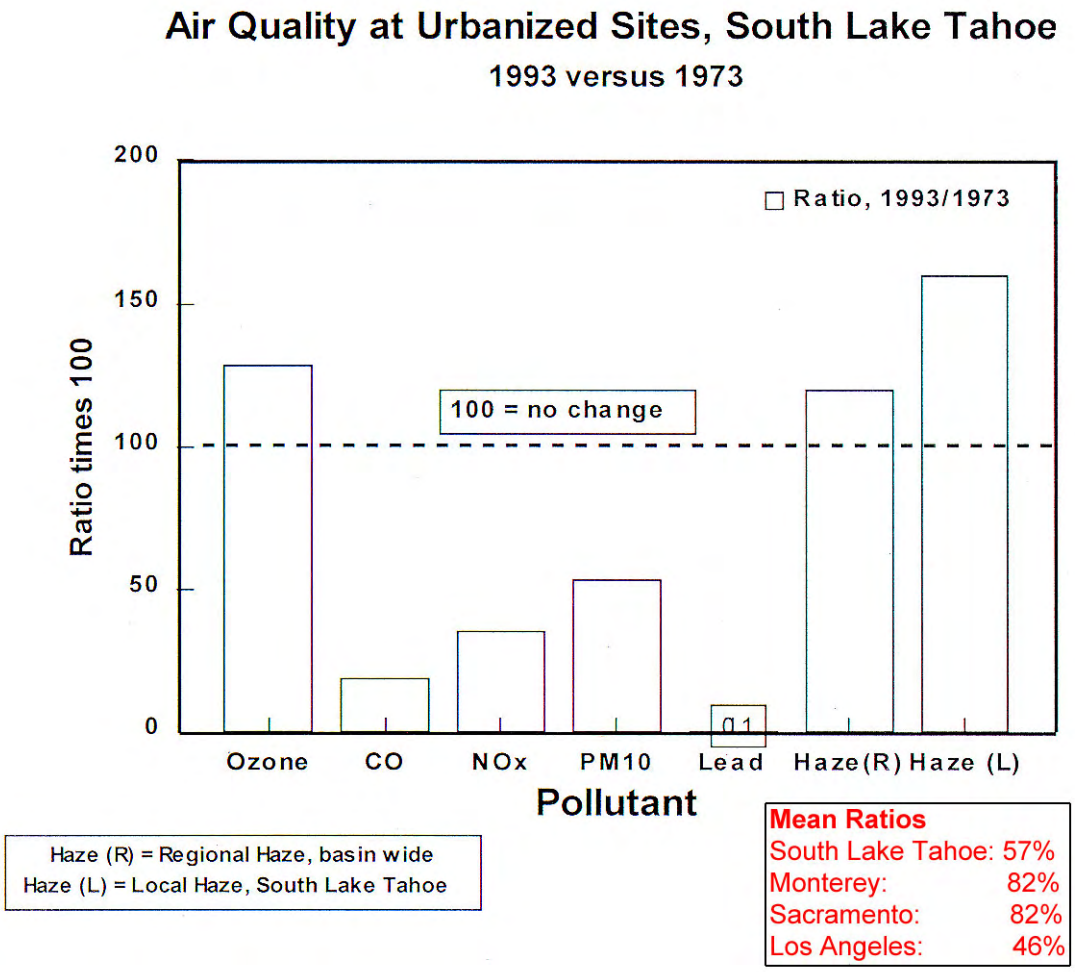


Figure 3-23—Change in concentration of pollutant and coefficient of haze at Lake Tahoe from 1973 to 1993. Note sharp reduction in CO, NO_x, PM_{10}, and lead over this period. Ozone increase at South Lake Tahoe is unique to urbanized areas over this period, possibly resulting from increased development of the foothill communities east of Sacramento.

magnitude similar to modeling scenarios would lead to qualitative validation of model output for the scenarios. As part of this validation effort, we were able to perform one limited experiment during the course of the assessment process for prescribed fire modeling. On June 9, 1999, a prescribed fire near Spooner Summit commenced. This fire, the Captain Pomin Prescribed Burn, consumed approximately 45 acres on June 9. The total planned burn area for this fire is 350 acres. For a fire of this size, the LTAM predicts (not shown, see historical fire output, Figure 3-24) a significant visibility reduction over Lake Tahoe for the inversion period, from sunrise until about 11 AM. Typically a west to southwest wind is present during the daytime, and most smoke will not directly affect the basin. However, in the late evening and early morning hours the inversion in the basin, as modeled by the "summer night" meteorological conditions in the LTAM, forces smoke to settle near the lake surface until the winds pick up again the following day. The LTAM preliminarily predicts that a 45-acre fire on the east side of the basin would obscure the west shore and mountains above during this inversion period. Photographs taken on the

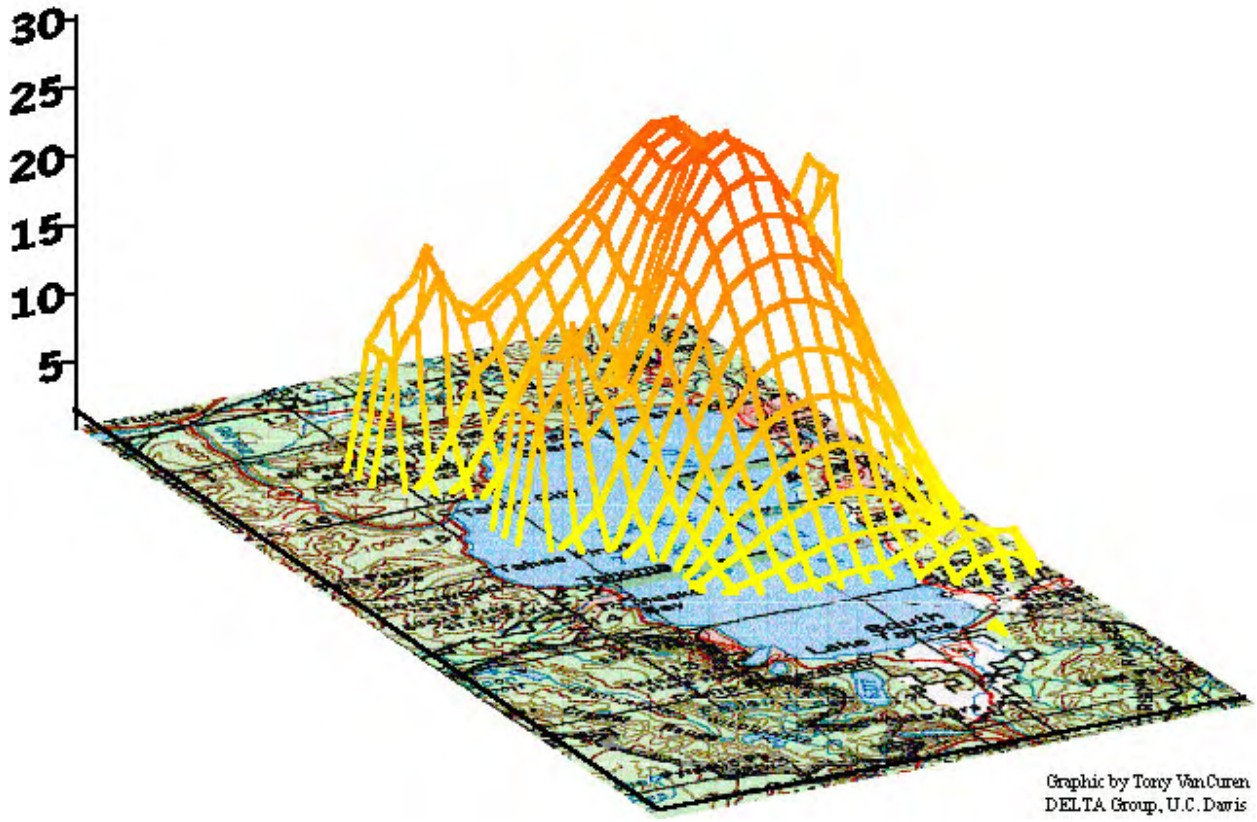


Figure 3-24—LTAM output for $PM_{2.5}$ concentration distribution in the Lake Tahoe basin (underlying map) from historical fire situation based on a 24-hour average. The inputs for this model run are three small wildfires (~10 acres), one in the Ward Creek Watershed, one in the forested area near Meeks Bay, and one near Sand Harbor on the east shore. The proposed federal 24-hour standard is 65 $\mu g/m^3$ for $PM_{2.5}$. The peak of 29 $\mu g/m^3$ is well below this standard and corresponds to a visibility range of more than 19 miles at lake level and more than 50 miles at ridge tops.

morning of June 10, 1999, from the lakeshore in Glenbrook, Nevada, qualitatively confirm this LTAM prediction (figures 3-25, 3-26, and 3-27). Furthermore, photographs taken from the Lake Tahoe overlook at Echo Summit on Highway 50 (Figure 3-28) indicate a rather uniform distribution of smoke over the lake, with a slightly greater density near the center. As discussed in Issue 1, Question 2, Section 4 for the hypothetical natural historical conditions, the LTAM predicts similar features. Most of the visible smoke from combustion is $PM_{2.5}$, due to the high efficiency for scattering light. Visible smoke then can be a good qualitative indicator of $PM_{2.5}$ concentration, which is what is modeled by the LTAM. At the time of this writing, quantitative mass measurements were unavailable for prescribed burns in the Tahoe basin. Future studies are expected to provide concentration and chemical composition of the smoke from fires that may have an impact on lake clarity and the ecosystem as a whole. Further research of this sort is sorely needed to determine the validity of any predictive model in general and the LTAM in particular.

Figure 3-25—Photograph of smoke from prescribed Captain Pomin fire looking southwest from Glenbrook, Nevada. The mountain range above the southwest shore is barely visible below Rubicon Peak, as preliminarily predicted by the LTAM (photo courtesy Steven S. Cliff).

Figure 3-26—June 10, 1999, photograph, looking northwest from Glenbrook, Nevada, showing the shoreline near Tahoe City completely obscured by smoke from prescribed Captain Pomin fire (photo courtesy Steven S. Cliff).

Figure 3-27—Photograph of west shore of Lake Tahoe, showing complete loss of visibility of the shoreline to the north and partial loss to the south. Taken from Glenbrook, Nevada, on June 10, 1999, following the prescribed Captain Pomin fire (photo courtesy Steven S. Cliff).

Figure 3-28—Photograph taken June 10, 1999, from Echo Summit. Smoke covering the Lake Tahoe basin the day following the 45-acre prescribed Captain Pomin fire near Spooner Summit reduced visibility over the lake below 15 miles.

Summary

The LTAM is designed for use as a heuristic tool to gather disparate sources of air quality data at Lake Tahoe into a consistent framework. The value of the LTAM is in its ability to predict air pollution impacts of both ambient conditions and specific source events. Sources of pollutants, such as fires, transportation, urban, space heating, and upwind transport can all be input into the model. Calculation of dispersion in the atmosphere and lake and forest deposition result from the LTAM. The most significant finding from the construction and use of the LTAM is that pollutants are most likely to deposit to the lake surface and hence potentially degrade lake clarity at times of intense inversion. Atmospheric inversion at Lake Tahoe is the most predominant meteorological condition during summer evenings and all day throughout the inter-storm winter period. Photographs taken during a recent prescribed burn near Spooner Summit preliminarily validate the predictions of the model. Although this validation is qualitative, it is the first approach to linking the predictive capabilities of the LTAM with empirical results from research studies. Further investigation of the source, transport, chemical transformation, and deposition mechanisms of atmospheric pollutants, both algal nutrients and fine particles, in the Lake Tahoe basin is imperative for integrating scientific and management-based models.

What are the scenarios that were developed for demonstration of the watershed models for the assessment, and what output is given by the LTAM?

Scenarios for watershed assessment modeling integration were developed to present the type of modeling results that are possible with single medium (in this case air quality) models designed specifically for the Lake Tahoe basin. The scenarios evaluated prescribed burns in the Ward Creek watershed on 40- and 20-year cycles occurring in October and a wildfire that would burn approximately 75 percent of the forested part of the Ward Creek watershed in August. In this modeling effort a number of parameters were derived that provide input to the LTAM.

The current integrated modeling scenario places prescribed burns in October for the Ward Creek watershed. Because October is the transition between summer and winter conditions, a combination of both meteorological regimes is represented. For the wildfire scenario, summer conditions are applied. No account is taken for specific meteorological conditions that may be present in a specific year, but rather the general LTAM meteorology for summer and winter.

Derivation of Model Input

Due to the fact that a wild or prescribed fire will dominate all other emission sources for particulate matter (PM) during October, road PM is set to 0 for the integrated fire scenario in the Ward Creek watershed. Urban emissions, however, are included and are derived from an estimated nonhighway traffic component plus the difference between the D. L. Bliss and South Lake Tahoe TRPA aerosol data. Following spring thaw, road aerosol emission is far from negligible. Model parameters for fire emission and loss rate are derived from a number of sources. Particulate emissions from fires is statistically derived from the USFS Grand Canyon Commission Fire Emission Project Database Model (VanCuren 1996). Data from 110 fires in the Lake Tahoe area dating back to 1980 were used to derive PM emission estimates. Forest and lake falloff parameters were derived from data collected during the 7,000+ acre/day Cleveland fire of 1992 (Figure 3-29).

Since the LTAM has a cell dimension of 2.56 km^2, emission numbers need to be calculated relative to the size of a theoretical “box” that has a two-dimensional area equivalent to one cell. The volume of the box is given by this area multiplied by the height of the air parcel within the box. In the case of both prescribed fires, the total area of the fires is less than one cell in the LTAM. For the wildfire, nearly eight full cells in the LTAM are used for the emission source. Derivation of pollutant emission factors involves calculating essentially three parameters, the volume of the box, wind speed, and particulate emission per unit area. The box volume is

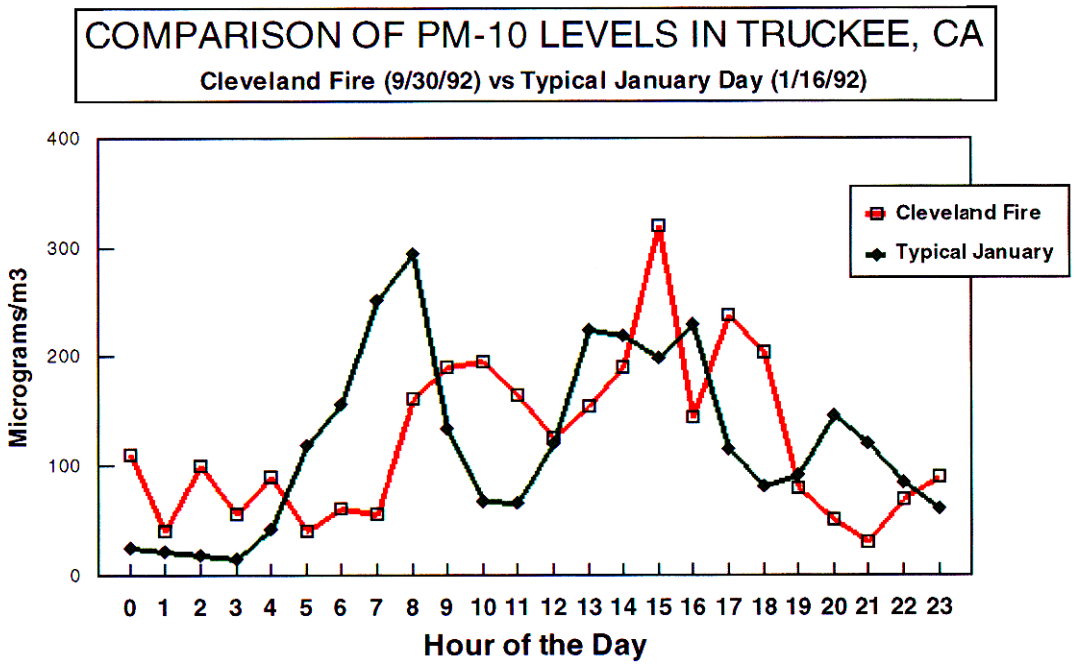


Figure 3-29—Diurnal concentration of $PM_{2.5}$ for a day during the 1992 Cleveland Fire and a typical winter day at Truckee, California. Note that on a typical winter day $PM_{2.5}$ concentration is equal in magnitude to the upwind 7,000-acre per day Cleveland Fire.

determined by area burned multiplied by the theoretical height of the box. Box height for PF1 is assumed to be 0.1 km, PF2 is 0.5 km, and WF is 3 km. These box heights are determined by observations of smoke from the various fire types. The wind speed is factored into the emission rate by the number of times clean air is transported into the box, i.e., at a wind rate of 1.6 km/hr, each cell in the LTAM would have an average air change of once per hour. Finally, emission per acre is determined as the average derived emission from the USFS Grand Canyon Commission Wildfire Emission Project Database Model (VanCuren 1996). For the current scenarios, this is determined to be 0.06 metric tons (MT) $PM_{2.5}$/acre, 0.06 MT PM_{10}/acre, and 0.09 MT TSP/acre. The error associated with these estimates is quite large, on the order of a factor of 10, but the LTAM predicted concentration based on a specific event (see previous section on validation) is accurate to within 20 percent, nevertheless. The total acreage of the Ward Creek watershed is 25.23 km^2 (6,234 acres), about 80 percent of which is forested. This gives 20.18 km^2 (4,986 acres) of forested area. The 40-year return burn period (2.5%/year) gives a fire size of 0.5 km^2 (124 acres), and the 20-year return burn period (5%/year) gives a fire size of 1.0 km^2 (248 acres). For the August wildfire, approximately 15 km^2 (3,700 acres) are burned, consuming 75 percent of forested area of the Ward Creek watershed.

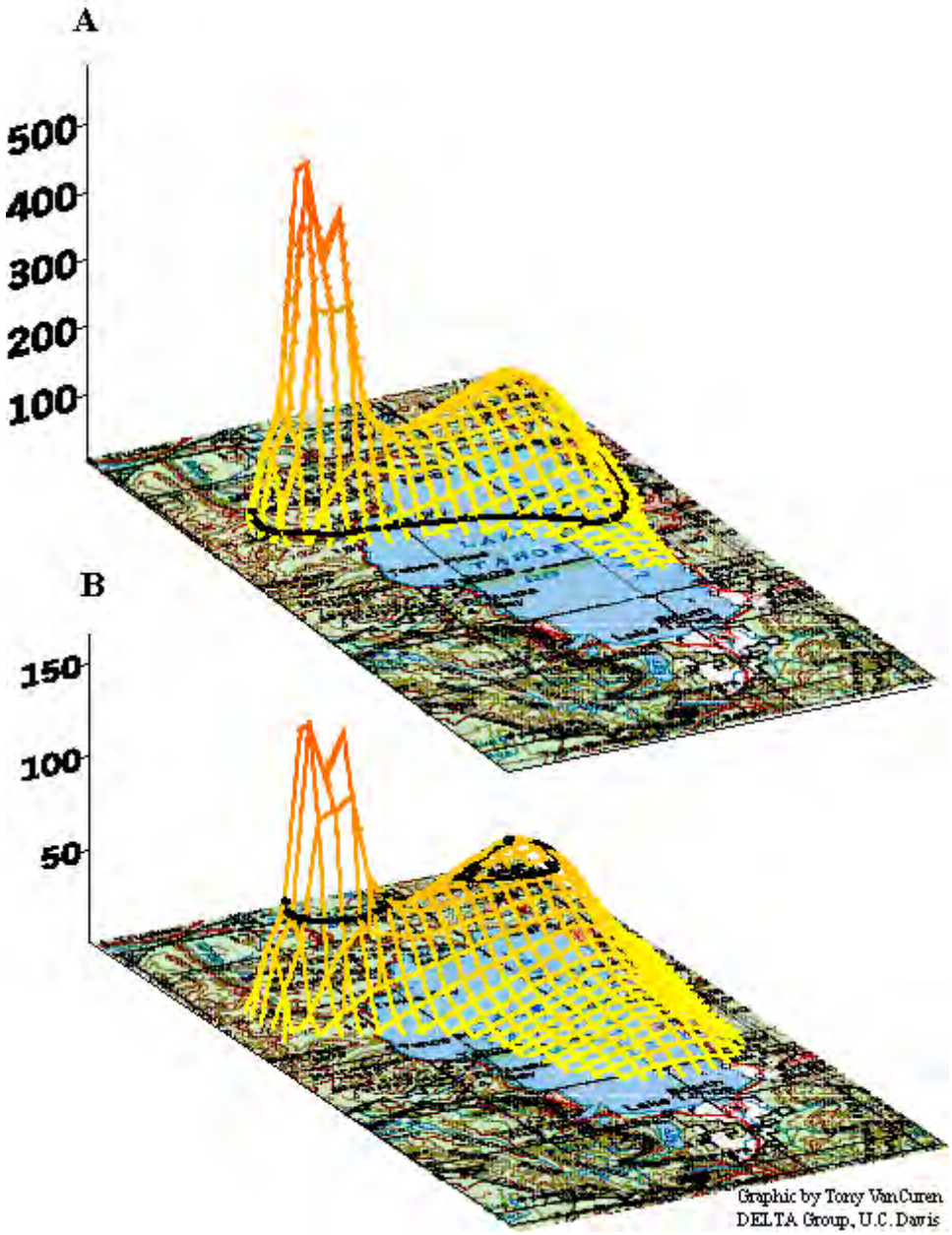
It is apparent from the emission estimates that over 90 percent of the PM_{10} falls in the $PM_{2.5}$ category. Furthermore, $PM_{2.5}$ is the primary pollutant effecting visibility, lake clarity, and human-health. For these reasons, the LTAM modeling output for these scenarios includes only $PM_{2.5}$. Although we focused on $PM_{2.5}$, using the LTAM it is possible to predict the concentration of a variety of pollutants across the basin. Other pollutants include TSP (total suspended particulate), NO_x, and hydrocarbons. Essentially any pollutant species that is known to be emitted from combustion can be examined.

Model Output for Scenario

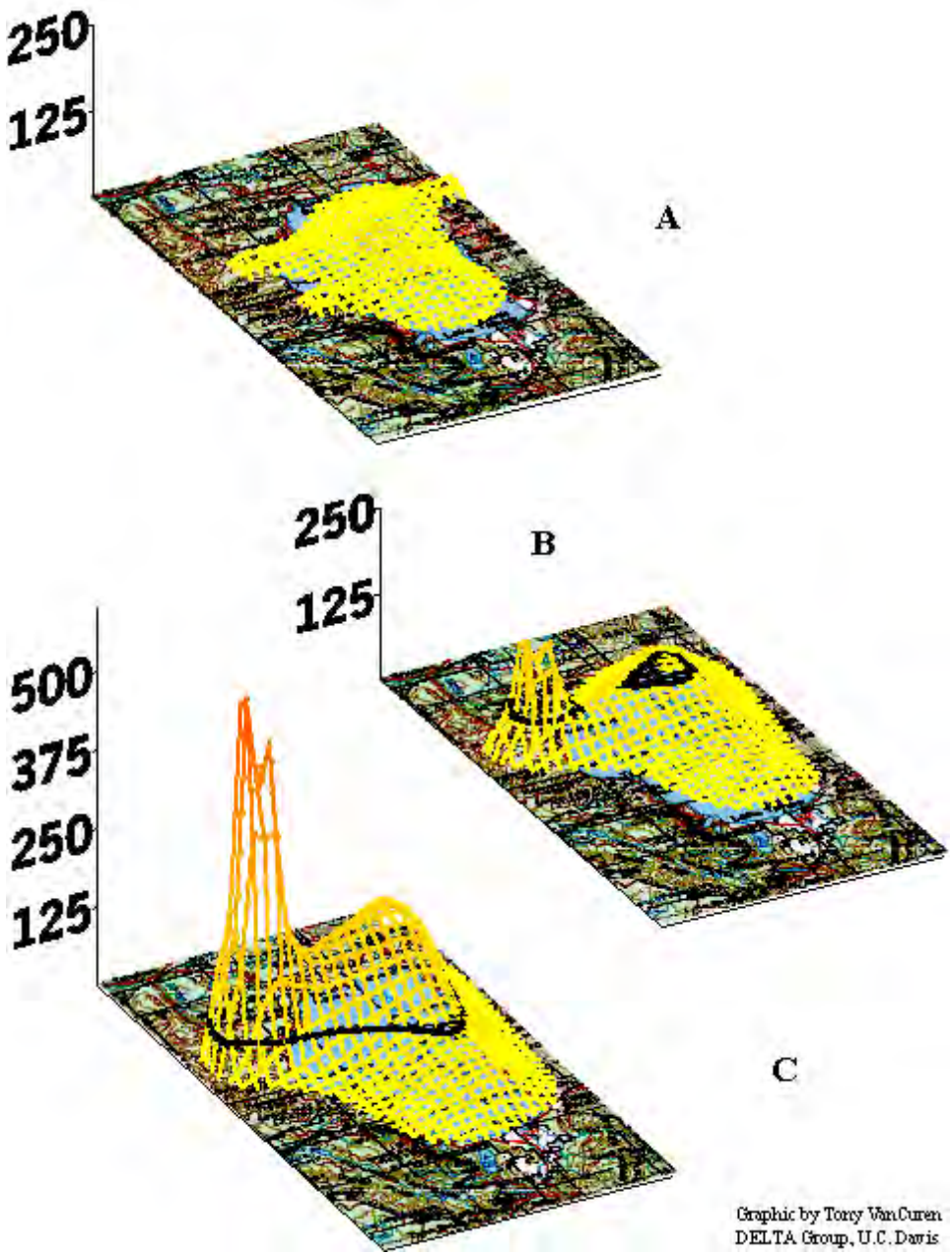
From the calculated emission parameters for the wildfire and prescribed fire scenarios, the LTAM calculates the falloff in smoke $PM_{2.5}$ across the basin. The resultant values from the LTAM are graphed as a concentration versus location and then are plotted over a map of the area represented by the model (Figure 3-4). Contrasted with the historical wildfire comparison (Figure 3-24), the LTAM is seen to predict massive violations of federal and state $PM_{2.5}$ standards for the 20-year return scenario (Figure 3-30a). The historical wildfire is an analysis of past conditions, based on a 40-year return in the basin divided among the total burn season, equaling about 30 acres burned per day in three small (10 acre) wildfires. The 40-year return scenario predicts localized violations for the October period (Figure 3-30b). A model run for the same scenario for a typical summer period (not shown) predicts fewer violations, mostly due to the increased ventilation of the basin during that time. A comparison of the three scenarios (excluding the large wildfire) is shown in Figure 3-31. The hypothetical wildfire during August, burning over 3,700 acres, is predicted to completely fill the basin and beyond with smoke (Figure 3-32). The output is broken up into three days of burning, with day one consuming about 60 percent of the acreage, day two at 25 percent, and day three at 15 percent. Some smoke carryover from the previous day is included in days two and three in the LTAM predictions. Although the wildfire burns an order of magnitude more land than the prescribed fires, the number of resultant violation days is predicted by the LTAM to be roughly equivalent. That is about two to three violation days for the 40-year fire, three days for the 20-year fire, and four to five days for the wildfire. The apparent discrepancy of this fact is due mostly to the increased ventilation of the basin during the late spring and summer. Furthermore, increased lofting of smoke in a wildfire results in impact at greater downwind distance than in a prescribed fire situation. The LTAM is capable of only limited predictions at this time. Further study of the impact of fire on the Lake Tahoe ecosystem, especially the impact of smoke on lake clarity, visibility, and human health, is necessary to better define parameters for integrated management models in general and the LTAM in particular.

Summary

The smoke concentration in the form of particulate matter with an aerodynamic diameter less than 2.5 micrometers ($PM_{2.5}$) has been evaluated by the LTAM for hypothetical wildfire and prescribed fires in the Ward Creek watershed. The result of this evaluation indicates that, for the prescribed fires, a fall burn is particularly troublesome from the standpoint of air quality. The atmospheric inversions that tend to be present during the fall inhibit ventilation of the Lake Tahoe basin and hence allow concentrations of $PM_{2.5}$ to build up. Currently, not enough is known about the chemical composition and speciation of prescribed fire smoke to evaluate the impact of these prescribed fires on the clarity of Lake Tahoe. It is known, however, that $PM_{2.5}$ is a pollutant from the perspective of human health. The potential for violations of federal, state, and basin air quality standards based on visibility is also expected from prescribed fire. Wildfire, whether natural or anthropogenic, burning in the summer at a time of great ventilation is predicted by the LTAM to violate all basin-wide air quality standards. Ground level peak concentration of $PM_{2.5}$ in the wildfire scenario is expected to be lower than the prescribed fires due to this increased ventilation of the basin in the summer and greater lofting of smoke in a large fire. A better evaluation of the impact of forest fires on ecosystem health at Lake Tahoe will require further study. It is imperative to understand the link between emission, transport, and deposition of smoke constituents throughout the basin to more effectively constrain integrated modeling tools for management use.



Figures 3-30a and 3-30b—$PM_{2.5}$ 24-hour average concentration from LTAM output superimposed on the basin map for prescribed fire scenario. The 20 year return (five percent per year, or 250 acres) is shown in 30a, and the 40-year return (2.5 percent per year, or 124 acres) in 30b. The black isoplith indicates the proposed federal 65-$\mu g/m^3$ limit. Figure 30a has a maximum concentration of about 500 $\mu g/m^3$ $PM_{2.5}$ with violations over the federal limit predicted for more than a third of the basin. Figure 30b shows predicted local violations near the fire source.



Figures 3-31a, 3-31b, and 3-31c—$PM_{2.5}$ concentration predictions from LTAM based on a 24-hour average superimposed on the basin map. Comparison of three fire scenarios in the Lake Tahoe basin. Top figure is the historical wildfire from Figure 24. Figures 31b and 31c are hypothetical prescribed fire scenarios located in the Ward Creek Watershed. Figure 31b is a 124-acre prescribed fire, and 31c is a 248-acre prescribed fire representing a 40- and 20-year total fire return time to the basin, respectively. The black isoplith is set at 65 $\mu g/m^3$, which is the proposed federal 24-hour standard for $PM_{2.5}$. The peak concentration for 31a, 31b, and 31c are 29, 165, and 500 $\mu g/m^3$, respectively.

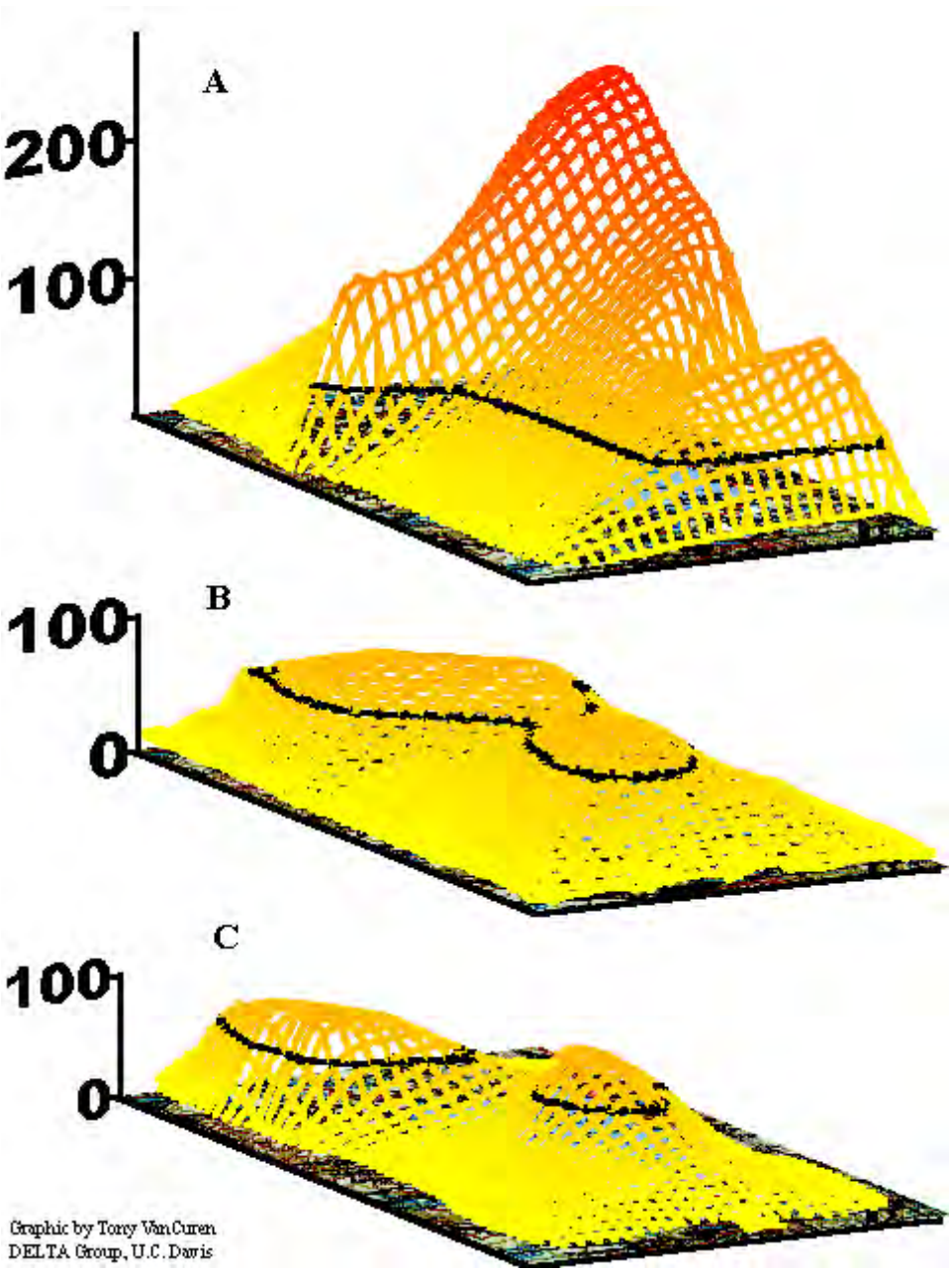


Figure 3-32—24-hour average $PM_{2.5}$ concentration LTAM output superimposed on the basin map for hypothetical wildfire (3,700 acres) in the Ward Creek watershed. The wildfire is broken up into three days of burning. Day 1 is 60 percent of the total acreage, day 2 is 25 percent, and day 3 is 15 percent. The black isoplith indicates the proposed federal limit of 65 $\mu g/m^3$ $PM_{2.5}$ 24-hour average. By day 3 the plume is breaking up as fire is theoretically suppressed. By day 4 the smoke is expected to drop below 65 $\mu g/m^3$ for the given scenario. Day 1 indicates a maximum $PM_{2.5}$ 24-hour average of 200 $\mu g/m^3$.

Issue 2: The Need to Determine Spatial Location and Natural versus Anthropogenic Origin of Pollution that Degrades Air Quality in the Lake Tahoe Basin

What are the relative contributions of in-basin versus out-of-basin air pollution sources, especially sources in the Sacramento Valley and western slopes of the Sierra Nevada, that affect the Lake Tahoe basin?

Air pollution at Lake Tahoe is implicated in a number of ecosystem impacts. Air quality within the basin is determined by both local and upwind sources. Most air pollutants measured in the Lake Tahoe basin are local in origin, with some important exceptions. Ozone in the summer is transported almost entirely from urban primary sources in the Sacramento Valley and damages Jeffrey pines in the basin. Fine particulate smoke, sulfate, and nitrates are transported efficiently from the Sacramento Valley each summer, providing roughly half of the mass and dominating the regional basin-wide haze. Smoke from wildfires on the western slope of the Sierra Nevada can blanket the basin, reducing visibility, violating health-based air standards, and causing algal blooms in the lake. An extensive discussion of in-basin versus out-of-basin sources of air pollution that contribute to air quality at Lake Tahoe is given in Issue 1 with regard to the development of the LTAM. In this section an overview of techniques that are available to determine local versus transported sources is presented.

Source Evaluation Techniques

There are several techniques that can be used to identify the source of an air pollutant in a specific area. The most confident identifications occur when two or more independent techniques can be used together. The tools that are available for understanding pollutant sources in the Tahoe basin include techniques based on source inventories, techniques based on transport (transport from meteorology, diffusion, and direct measurements along a transect), techniques based on pollutant transformation, techniques based on removal mechanisms, techniques based on receptor characteristics (both statistical and chemical mass balance methods), and techniques based on stable isotopic analysis.

Source evaluation techniques based on source inventories use emission inventories to give both the location and rate of emission of pollutants. The source rate and location information is given for both primary and secondary pollutants. A primary pollutant is a compound that is directly emitted. An example of a primary pollutant is carbon monoxide (CO), where CO is directly emitted from incomplete combustion of hydrocarbons. A secondary pollutant is an atmospheric compound that is made in a reaction during transport. Typically, both precursor species and sunlight are required for this transformation to occur. Ozone (O_3) is a secondary pollutant in that it is formed as a product of the oxidation of hydrocarbons in the presence of NO_x. It is known, for example, that almost all sulfur dioxide (SO_2) gaseous emissions in northern California come from a small area of oil refineries near the Carquinez Strait. Measurement of pollutant concentration at Lake Tahoe allows certain transport parameters to be estimated when the source is as unambiguous as in the case of SO_2. Furthermore, emissions can vary in time, and this aids in identifying the specific source. This type of identification is illustrated by the correlation of highway pollutants with traffic volume, as long as meteorology is included.

Another tool available for determining sources are techniques based on transport of pollutants. Meteorology can be used for identifying sources by determining the trajectory of an air parcel with time. Forward and back trajectories are often used to determine the traveled path of an air parcel from either source to receptor or receptor to source, respectively. Also, local gradients, such as pollutants measured across a road, or transport gradients for greater distances can be useful. Typically local gradients are dramatic in variation, whereas transport gradients are more subtle. Diffusion of an air parcel containing specific pollutants by lateral wind variability can smooth out the source profile. An example of this smoothing is seen with both sulfate and ozone at Lake Tahoe. Both sulfate and ozone are derived from upwind sources and are essentially uniform across the basin. Alternatively, local sources,

both roadway and urban, strongly correlate with the density of traffic and number of dwellings.

Direct measurement of a pollutant species along a transport corridor can be used to measure compounds as they move from source to receptor. In 1978, CARB/UCD studies placed stations from the Bay Area to Lake Tahoe and measured sulfates along the entire trajectory. Sulfates, derived mostly from Bay Area oil refineries, were found to be transported to Lake Tahoe from outside the basin. Also, beginning in 1989, a station was established at Bliss along the transport vector from the Sacramento Valley to South Lake Tahoe, allowing easy separation of transported particles from local particles in this one area.

Another useful technique for evaluating pollutant sources is by examining pollutant transformation. Secondary pollutants, such as ozone, take time to be converted from precursor to product. Typically, although not always, these pollutant transformations require such conditions as sunlight. This is illustrated at Lake Tahoe by ozone levels that often peak in the late evening, when the sun has set. Because sunlight and time are both required to convert hydrocarbons and NO_x to O_3, this is robust support for upwind sources. This technique, coupled with the relatively uniform distribution seen at other times, as mentioned earlier, strongly suggest upwind sources.

Identification of sources based on removal mechanisms or sinks is often useful. Some pollutants are rapidly removed from the air once they are away from their sources. For example, coarse soil particles settle rapidly to the ground, while fine soil particles can travel great distances. At Lake Tahoe this is especially important due to the role that fine particles play in scattering light both in the lake, where they reduce clarity, and in the air, where they reduce visibility. Some pollutants, transported from a great distance, can have a large impact on the basin.

Also available for determining pollutant sources are receptor characteristics. Statistical correlations can be made between pollutants of known sources and pollutants with several possible sources. For example, in an air sample fine lead (from studies conducted before leaded gasoline was banned), which comes only from cars, can be evaluated with gaseous NO_x, which has several possible sources. A correlation can be strong evidence that most of the NO_x is derived from automobiles. Chemical mass balance correlation, where the source of a species at a receptor site can be determined by analyzing tracer elements, is a more complicated method of determining source characteristics. An example of this is the unique chloride-to-sulfate ratio derived from oceanic emission. Based on its unique signature, the contribution of sea spray to an air sample can be statistically determined. This may be a technique that can be used at Tahoe to determine smoke sources by using a unique tracer for different types of smoke, such as pine versus brush.

An additional technique available for determining sources of pollutants at Lake Tahoe is stable isotopic analysis of pollutant compounds. Because the isotopic composition of an atmospheric species is set by the precursors and processes that form the molecule, a fingerprint for a source can be determined. For instance, SO_2 from Bay Area refineries will have a distinct isotopic signature for both sulfur and oxygen. As this species is transported, however, oxidation and coagulation will occur, producing sulfate particles. These sulfate particles will likely retain a signature of the original process, on which the chemical transformation signature is superimposed. In the case of nitrogenous species at Lake Tahoe this would be particularly useful in determining both sources and transformation mechanisms (oxidation). The relative influence of transported and locally generated nitrogenous nutrients then could be assessed. Although a technically difficult process, stable isotopic analysis can simplify the process of determining the impacts of in-basin and out-of-basin pollutant sources, especially when combined with other analysis techniques.

Summary

In all, there are a number of techniques available for determining the sources of air pollutants. Although a moderate accounting of pollutants has been conducted for the Lake Tahoe basin, a gap in the knowledge exists. Lacking in the information database is a connection between the

concentration of pollutants in air and the deposition to the Lake Tahoe surface. It is unclear what is the source of phosphorous seen in the deposition studies reported by Jassby et al. (1994). Furthermore, agreement between the deposition of pollutants reported by Jassby et al., and atmospheric measurements does not exist. Not only are the sources of phosphorous unknown, the concentration of phosphorous in the measured particles is not adequate to explain the deposition results. Past atmospheric studies appear to have excluded the collection and analysis of this important species. A complete understanding of the connection between lake and air relies on these deposition data. Finally, measurements of prescribed fire emissions are necessary to determine the relative influence of these large local pollutant sources versus transported pollutants on the Lake Tahoe ecosystem.

What are the relative impacts of natural versus anthropogenic sources, especially the relative contribution of smoke from wildfires versus prescribed fires?

Atmospheric pollutants that contribute to overall air quality at Lake Tahoe derive from both natural and anthropogenic sources. For instance, wildfires, volatile organic compound emissions from trees, and windblown dust all are natural phenomena. In contrast, automotive and industrial pollutants, prescribed fire smoke, and human-caused wildfire smoke all derive from anthropogenic sources. Impacts from natural wildfires is not seen today because numerous, small noncrown fires in summer and fall have not been seen since the mid-19th century. The prediction would have been for spotty but persistent smoke in relatively low concentrations around the basin. Present day wildfires are almost always started by humans and are always enhanced by humans due to fuel buildup resulting from fire suppression. Wildfires are infrequent but have massive impacts on the Lake Tahoe basin, degrading visibility, causing algal blooms in the lake, and probably violating state and proposed federal air quality standards. There are few air quality data on the impacts of prescribed fire beyond the obvious smoke plumes seen near such burns.

Results from the LTAM indicate that large smoke contributions to pollution will be seen for prescribed and wildfire scenarios (figures 3-30 and 3-32). The relative contribution of these sources will depend on individual fire scenarios, such as the time of year, acreage burned, specific meteorology, and composition of fuel. This question was extensively addressed in Cahill (1996); some of that material is presented here.

Sierran Smoke Sources

It is surprisingly difficult to establish the effects of various independent smoke sources on air quality in the Sierra Nevada. Smoke has a visual impact out of proportion to its mass, so that smoke levels must be extreme before the record of particulate mass reflects a major impact. Yet the only 24-hour federal particulate standard is for particle mass below 10 micrometers in diameter (PM_{10}), which is not violated until visibility drops to about two miles. Most of the air particulate sampling in the Sierra Nevada measures only PM_{10} mass, thus is of limited use in identifying small and moderate smoke impacts. These sites operate only on a one-day-in-six cycle and, due to urban locations, are of little use to establish nonurban smoke levels. Furthermore, data on how many acres are burned each day from either wildfires or prescribed burns are often difficult to access. Meteorological measurements in the mountains are scarce and terrain effects are major.

The IMPROVE database is somewhat better in several regards. The measurement units are for $PM_{2.5}$, which is a better match to the size of smoke. The sites operate Wednesday and Saturday, in nonurban, nonvalley locations and have full meteorological, chemical, and optical analysis. However, there are only two such sites in the Sierra Nevada—Sequoia and Yosemite National Parks. Fortunately, the paired stations at Lake Tahoe, operated for TRPA using full IMPROVE protocols, provide a very important third site, as well as an invaluable nonurban to urban comparison. In addition, data are extended by using similar sites in the Cascade Range and San Bernardino Mountains.

Analysis of aerosol data from several sites in the Sierra Nevada indicates that the most severe impacts on air quality occur from large wildfires and shows little effect of controlled fires at remote locations. Using data from the IMPROVE air sampler at Turtleback Dome in Yosemite National Park as an example (Figure 3-33), the highest levels of particulate pollution occurred during a prescribed natural fire that burned in the park from July 3 to August 18, 1994. On only one occasion, however, did the pollution exceed the state air quality standard of 50 $\mu g/m^3$ for PM_{10}. The presence of smoke at the site during this episode is evident from the unusually high peaks in nonsoil potassium (K-non), a tracer of biomass smoke, and from human observations. Relatively low levels of particulate matter were seen during the subsequent fall season when the majority of agricultural waste burning is occurring in the San Joaquin Valley, as well as controlled burning in nearby forests for fire suppression and silviculture.

In contrast, frequent high levels of PM_{10} occur in the heavily developed Yosemite Village (in Yosemite Valley) during the same period, even when no large fires are burning in the area. Many small local sources (campfires, fireplaces, and vehicles) and the micrometeorology of the valley, which tends to trap air under a nighttime inversion, result in a high background level of pollution.

Another comparison of local anthropogenic sources versus wildfires and controlled burns occurs in the Tahoe basin. Air quality data taken near the relatively urbanized Highway 50 corridor in South Lake Tahoe show high levels of aerosol pollution in the winter. Large peaks occur in both organic matter and in K-non, indicating wood smoke as the source. At D. L. Bliss State Park, located in a largely undeveloped area where there are few fireplaces, the winter is the cleanest season. This suggests that residential wood combustion is the primary source at 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

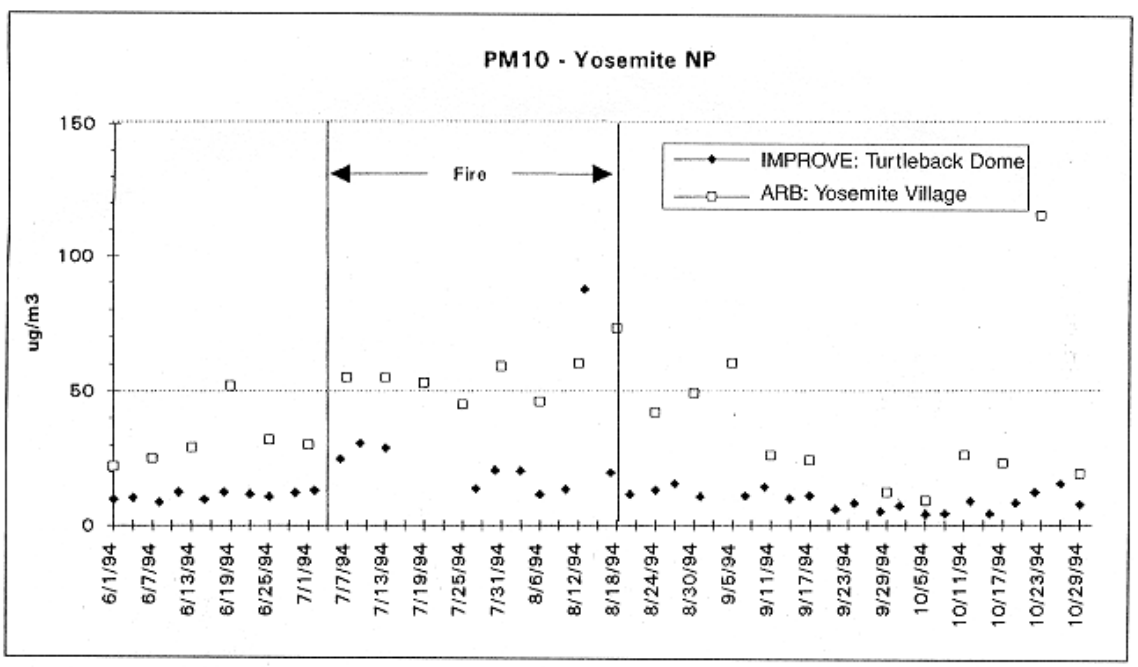


Figure 3-33—PM_{10} concentrations in Yosemite Village, Yosemite National Park, from the Turtleback Dome prescribed fire in 1994 from IMPROVE and ARB samplers. The parameters derived from this data are used for PF1 values in the LTAM.

controlled burning in the surrounding national forests is at its peak. But the smoke levels, even under these conditions, are far lower than the winter peaks, roughly 20 percent, at South Lake Tahoe and are of much shorter duration.

A final direct comparison between wildfires and residential wood burning was made in Cahill et al. (1997) for Truckee, California. The availability of a new type of particulate measuring unit, a TEOM, allowed mass to be measured hourly. The intense Cleveland fire of 1992 was located south of Interstate 80 and upwind of Truckee. This fire burned 5,500 acres on September 29, 7,000 acres on September 30, and 7,500 acres on October 1, when a light rainfall (0.1 inch) greatly aided fire suppression, limiting further acreage to roughly 3,500 acres until the fire was declared out about one week later (McKey 1995). The smoke levels were comparable for these two cases (121 $\mu g/m^3$ for the Cleveland fire and 124 $\mu g/m^3$ for a typical January day), but one has to remember that the Cleveland fire lasted for only a few days, while winter smoke episodes at Truckee are extremely common under the characteristic winter subsidence inversion found in almost all high mountain valleys. The peak winter day level in January 1992 was 179 $\mu g/m^3$, measured by TEOM, but the TEOM probably understates the equivalent filter mass by 30 percent because the TEOM filter is heated, which drives off some of the water. Thus, in terms of person-dose, a typical winter day level is at least a factor of 10 or greater more important to health than a major local forest fire.

On the same day as the Truckee data, September 30, 1992, samples were taken at Bliss State Park as part of the regular Wednesday-Saturday IMPROVE-compatible protocol for TRPA. Bliss was not affected nearly as much as Truckee because the wind was driving the smoke northeast. However, the level of PM_{10} was 13 $\mu g/m^3$ versus 121 $\mu g/m^3$ for Truckee, during the Cleveland fire. Even so, the September 30 reading was the highest PM_{10} recorded on 16 sampling days between September 2 and November 30, 1992, more than double the annual average of 5.85 $\mu g/m^3$ recorded 1992-1993. The corresponding fine mass was 5.35 $\mu g/m^3$ versus an annual average of 3.39 $\mu g/m^3$. A strong nitrate signal was received, in fact the highest level seen all year, at 1.45 $\mu g/m^3$ versus an annual average of 0.29 $\mu g/m^3$. This raises the question whether a significant component of the strong nitrate peak seen in South Lake Tahoe in winter could be from residential combustion of pine wood. Another more likely possibility is that the nitrate resulted from the volatilization of dry deposited nitrate on pine needles. Other species reached the highest level during the fire, including trace amounts of chloride, arsenic, selenium, and bromine. The K-non smoke tracer reached its second highest level on June 30, supporting the theory that much of the smoke in the mountains was from valley grasses, which have a K-non/mass ratio of at least ten times that of pine.

The results of the Cleveland fire help put into context the smoke from controlled burns, which for an entire season might total 7,000 acres, roughly as much as was consumed per day in the Cleveland fire. In addition, the Cleveland fire occurred at a dry, hot period of the summer, without the meteorological mitigation built into controlled burns. Hence, the absence of any obvious signature due to controlled burns at Bliss, along with only one day of moderate impact at Yosemite, now can be readily understood because so little fuel is burned per day, as compared to the uncontrolled Cleveland fire.

The relative importance to human health of local wood burning, as compared to forest fires, can be explained by higher population densities in urban areas, the regular pattern of residential wood fires, the penchant for these urbanized areas to be in valleys rather than ridges, and the common nighttime inversions that trap smoke close to the ground. Wildfires, by their very nature, generate lots of heat and tend to loft much of their pollutant load into the sky.

The smoke produced by biomass combustion is composed of water vapor, other gases, and particles less than 2.5 μm in diameter ($PM_{2.5}$), but a significant amount of larger particles also may be produced by large intense fires due to entrainment of soil and partially combusted matter in the strong updrafts. Significantly larger particles present little threat to health or visibility and typically do not persist in the atmosphere for more than a few

hours before they settle out due to gravity. Fine particles, $PM_{2.5}$, however, are very effective in reducing visibility because they scatter light and aid the condensation of water vapor in the air. These smaller particles also contain a significant quantity of organic compounds known collectively as polycyclic aromatic hydrocarbons (PAH), which include a number of toxic and potentially carcinogenic substances. Because the fine particles are readily inhaled and retained in the lungs and may settle onto the surface of vegetation, increased concentrations of smoke represent a potential hazard to both human health (Larson and Koenig 1994) and the environment. These concerns are not limited to emissions from forest fires. Research data indicate that burning grasses, agricultural wastes, and other types of wood produce even higher concentrations of PAHs (Jenkins et al. 1995).

Wood burning emits a variety of gaseous pollutants (Jenkins et al. 1993). These are primarily composed of CO_2 and H_2O, with the remainder dominated by CO and a variety of hydrocarbons, including PAHs. Because CO is relatively inert and disperses readily, it should not have any significant impact on air quality beyond the immediate area of the fire. Hydrocarbons, on the other hand, can be transported over large areas and contribute to ozone formation in the presence of other pollutants. NO_x also is produced, as in all combustion, but in relatively small concentrations in comparison to their emissions from vehicles and industrial sources.

Evidence exists that part of the water of combustion of wood smoke may be trapped in the smoke, especially in cold, humid, winter conditions (Molenar 1994) and seen also in the 30 percent difference between TEOM and standard PM_{10} filters (above). If even a small fraction of the water is trapped, it can greatly raise the smoke mass. More detailed analyses are needed before this can be resolved. Nevertheless, a certain caution should be retained about ways to reduce wood smoke by reducing temperature of combustion and air flow, as opposed to an oxygen-rich open flame. Low temperature smoke is far more chemically complicated than high temperature smoke, retaining compounds that are known mutagenic (and perhaps carcinogenic) agents.

Autumn 1995 saw a good deal of activity in the area of fire pollution. That fall was exceptionally dry, with the first significant rain occurring in early December. The meteorology was stable, with weak winds and strong inversions forming in the Central Valley. Several prescribed natural fires and controlled burns persisted into periods of poor ventilation, with major smoke impacts on local communities. This occurred for fires in and near Sequoia National Park, which totaled about 9,000 acres by early December. Prescribed fires were ignited near Mineral King and in a chaparral zone about 10 miles upslope of Three Rivers. Heavy smoke was recorded in local communities, resulting in four violations of the 150 $\mu g/m^3$ federal 24-hour PM_{10} regulations, with the maximum value of 194 $\mu g/m^3$ (Ewell 1995). Another fire burned for about a month in the Lake Tahoe basin, in Bliss State Park near the TRPA aerosol site. Smoke impacts were regularly reported (Mahern 1996). Both of these fires represent patterns of prescribed and controlled burns that may become more likely in the future, and the experience gathered in these events will be useful in avoiding such impacts. Clearly, the concentration of so much burn acreage in a single watershed of air basin at times of poor ventilation resulted in unacceptable levels of smoke, although the anomalous weather of fall 1995 was a major factor in these episodes.

Finally, there was a major wild-fire/prescribed fire workshop sponsored by the WESTAR Council, an association of air resource agencies from western states, Alaska to the Dakotas, in San Francisco from November 27 to 29, 1995. Recommendations of this meeting have several points of interest (WESTAR 1995). One of these recommendations was made by a speaker from the US EPA on separating smoke from “ecological burns” and “activity burns” and possible trade-offs against wildfire smoke. The logic is that the ecological burns are really a way of avoiding future smoke from the much more serious crowning wildfires, as well as a way to maintain a healthy forest. The consensus also was reached that the nuisance effects of smoke, including visibility reduction, will become more important as a

constraint on burning than possible violations of federal fine particulate air quality standards. In the Lake Tahoe basin specifically, however, TRPA visibility violations are an important constraint on prescribed burning.

Overall, current data suggest that controlled forest burns are not as significant a source of particulate mass in populated areas of the Sierra Nevada as residential wood combustion and campfires. Large wildfires produce severe short-term impacts on air quality, but because they are rare, average smoke dose to individuals is generally limited. 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 significant threat to regional air quality as measured by fine particulate mass. The obvious exception is for some local visibility reduction, but this must be compared to improved air quality by decreasing the impacts of major wildfires. Given that fire is a natural part of the Sierra Nevada ecosystem (Phillips 1995), the beneficial effects on the Sierra Nevada ecosystem of increased fire use should not result in widespread violations of state or federal fine particle health standards. This rule, however, appears not to hold in the Lake Tahoe basin, according to the model results of the LTAM (Figure 3-31).

The very real problems of perceived smoke and visibility reduction must be addressed, however. One way is to couple the presence of modest summer smoke with the overall health of the forest and the reduced chances of major wildfires, which drastically reduce visibility and increase direct and indirect health effects. The other is to ascertain the relationship between visibility reduction and smoke mass, showing that even in visibly dense smoke, mass loadings are modest. Using results of studies of Oregon and Washington fires (Radke et al. 1990), a relationship can be measured. Visibility due to smoke must be reduced to 3.0 +/- 1.8 km (1.9 +/- 1.1 mi) before one reaches the federal particulate air quality standard of 150 $\mu g/m^3$ six miles before one reaches the California standard of 50 $\mu g/m^3$. The same relationship is found for IMPROVE's fine ($D_p < 2.5$ µm) particulate mass. A best fit between visibility and mean annual mass at forty-four sites gives 3.0 kilometers (1.9 miles) for the federal standard of 150 $\mu g/m^3$, assuming no contribution from particles greater 2.5µm diameter (Copeland 1995). The corresponding visibility at the 50 $\mu g/m^3$ California standard is 9.1 km (5.7 miles). The problem of visibility is compounded by the fact that for fires that occur in scenic areas, where visibility reductions are obvious. The plumes tend to be well above the ground, which makes them more visible and reduces ground level mass concentrations. The same effects do not occur for the even greater smoke densities in such towns as Truckee during the winter, for example, because the densely populated core of the town is less than one mile long.

There are also indirect effects of fires, in which they act as a means of transporting materials from one location to another. An example is agricultural burning in the central valleys of California. The mass of smoke by itself may not be a serious factor in terms of particulate mass, but when smoke affects cities, asthmatics are more likely to seek medical attention (Cahill et al. 1998). The answer appears to be in the reactions of sensitive populations to all the other materials lofted into the atmosphere with the smoke, which in the valleys include pollens, fungal spores, partially pyrolized pesticides and herbicides, and other components.

Summary

Questions regarding the impact of smoke in the Sierra are difficult to resolve based on limited compositional and transport data on this source. In the Lake Tahoe basin, knowledge is lacking for meteorology for much of the lake, as well as deposition to the lake surface. Furthermore, few measurements have been made of emissions from wildfires and prescribed fires for both mass and chemistry. The LTAM would greatly benefit from increased knowledge of these parameters. Large wildfires are reported to affect Lake Tahoe by

causing algal blooms in the lake. The impact of prescribed fire, however, is relatively unknown. Other atmospheric pollutants, such as NO_x, O_3, sulfate, and fine particles, also affect the basin. These pollutants are discussed in Issue 1 of this chapter.

How has air quality changed from prehistoric to present times?

Historically, air quality at Lake Tahoe has been excellent in winter and spring and is somewhat degraded in summer and fall from persistent small wildfires burning in the basin and on the western slopes of the Sierra Nevada. The most common pollutant, ozone, was elevated in summer due to transport into the basin from the Sacramento Valley but at levels that were still quite low (0.02 to 0.03 ppm).

There is a paucity of data on factors within the Sierra Nevada that affected air quality in prehistoric times. From historical data on fires and the natural timing of lightning-induced fires, we can infer two to four times as much area burned on an average summer day than in present times, with removal of timber plus present-day catastrophic fires redressing the biomass balance. Thus, it is expected that there was much more summer smoke in the past and less smoke in spring and fall, the time where prescribed natural fires and controlled burns are now encouraged. An example can be found in the Blue Mountains of northeastern Oregon, which were noted and named in the past for having much fire smoke commonly present in the summer.

The extent of transport of smoke into the Sierra Nevada from the Central Valley, a major factor at present, is not known from presettlement times. It may have been less than at present, based on statements on what the explorers observed, however, native Americans were known to encourage fires to favor generation of oaks and for other purposes.

In an attempt to derive the extent of presettlement smoke at Lake Tahoe, we can use records on burn frequency and location of wildfires at Lake Tahoe derived from such data as tree ring scars. Reburn rates vary widely in the basin, from high frequency on the eastern shore to low frequency in the moist western shore, and these will be incorporated in the model runs when available. An assumption can be made that the entire forested area burned once in 40 years, generally in the form of low intensity, lightning-initiated fires from May through October. Thus, we can estimate that 2.5 percent of the forested area, totaling about 156,000 acres, will be burned each year—about 3,900 acres/year. A natural burn period of five months (May through October, with the first and last months partial weighting) gives a burn rate of roughly 25 to 30 acres/day. Results from modeling the historical wildfire scenario from the LTAM (Figure 3-24) indicate that visibility would be greater than approximately 32 kilometers (20 miles) in the early morning within the basin. After inversion breakup at about 11 AM each day during the burn period, visibility would again increase to bring the north and south shores into view. If these preliminary modeling results are correct, historical wildfires would not have exceeded the current TRPA visibility threshold of at least 26 kilometers (16 miles) for at least 90 percent of the year.

Historical burns generally occurred at times of excellent air transport so that the smoke was rapidly diluted and transported across and out of the basin during the days. At night, however, the common inversion would pull the smoke downslope and over the lake so that each morning there would be smoke present at many areas of the lake. This persisted until the late morning winds re-established the daytime transport pattern. The efficient summer transport mechanisms, natural sources of hydrocarbons and oxides of nitrogen in the Sacramento Valley and typical summer high temperatures, lead to the prediction that there was significant ozone on the western slope of the Sierra Nevada that would in part be transported into the Lake Tahoe basin. These levels were probably in the range of 0.03 to 0.04 ppm, but during short periods of very high foothill temperature, they might be significantly higher.

Historic Air Quality

In early historic periods, there was extensive logging in the basin. This reduced natural wildfires by removing the forest but added smoke from habitat and logging activities. Historical photographs of the Lake Tahoe area often show smoke. However, at the time of these pictures (late 19th century)

massive human impact was evident as this was the peak of the Comstock lumbering period. In the early 20th century, the Lake Tahoe basin probably reached a minimum in smoke contamination. The forest was essentially gone and not yet regrown, and the USFS initiated a policy of fighting fires. Local habitation was very low and mostly in summer when smoke removal was efficient (E. B. Scott 1957).

The summer of 1973 saw the beginning of large-scale, reliable measurements of gaseous and particulate pollution at Lake Tahoe (CARB 1974). These data were analyzed for the CARB (Cahill et al. 1977) and led to an evaluation of the in-basin and out-of-basin sources. The continuous record of the CARB site at South Lake Tahoe can be used to compare gaseous air pollutants at South Lake Tahoe, 1973 versus 1993. Figure 3-23 compares the 1973 values of ozone, carbon monoxide, oxides of nitrogen, PM_{10} mass, and lead to the 1993 values. Some averaging of South Lake Tahoe sites from 1973 was needed to compare to the present CARB Sandy Way site. In general great reductions in most pollutants has been achieved, the sole exception being ozone which has risen roughly 30 percent in the past 20 years. This is an exception to a general California trend because all other sites with consistent records, including Sacramento, show ozone decreases. The present hypothesis is that the rapid growth in the foothills of El Dorado and Placer counties is adding ozone precursor pollutants directly into the transport corridors to Lake Tahoe; this is partially confirmed by the evening ozone peaks, often after the sun has set. On the same figure (Figure 3-23), the mean pollutant reductions for other California cites, Monterey (to 82 percent of the 1973 value), Sacramento (also 82 percent) and Los Angeles (46 percent), as compared to South Lake Tahoe (57 percent), were added. These reductions were achieved despite large increases in population and a doubling of vehicle miles traveled at most California sites. On the same plot is a comparison of haze, 1981 versus 1994 (Molenar et al. 1994) derived from the TRPA paired sites at Emerald Bay (Bliss State Park) and South Lake Tahoe. The regional haze, Haze (R) refers to the basin wide haze, the local haze, Haze (L), refers to South Lake Tahoe. There is a 25 percent increase in regional haze and a 65 percent increase in local haze in this period. Haze is dominated by fine ($PM_{2.5}$) particles, for which no 1973 readings were available. However, analysis of a smoke tracer, K-non, from the 1979 CARB/UCD report also shows a significant increase in smoke, from 1978 to 1994, in support of this observation.

Summary

In order to understand the change in air quality at Lake Tahoe, a careful examination of trend data is needed. Trend information is becoming available from the paired TRPA sites at Bliss State Park and South Lake Tahoe, and these should be carefully averaged to obtain trends in fine particles from 1989 to 1999 and beyond. Obtaining air quality data prior to the published studies by the CARB, NDEP, and UC Davis is difficult at best. Sediment records in the lake coupled with modern data may provide some information about atmospheric deposition to the surface over time. Presently, scaling of current air data to the recent historical past with the aid of the LTAM is the best resource available for determining air quality changes at Lake Tahoe.

How does air quality degradation generated within the basin affect downwind recipient areas, such as the Carson Valley?

Air quality in the Lake Tahoe basin is typically quite good, but some locally generated pollutants may have impacts beyond the watershed boundary. Although little work has addressed what specific impact basin air quality has on downwind area, the general meteorology at Lake Tahoe leads to conclusions regarding potential transport out of the basin and its impact on downwind sites. In the fall, winter, and spring, there are typically no downwind air quality impacts due to persistent inversions within the basin and weak downwind transport. In the summer, however, basin-generated gaseous pollutants transport readily downwind, with perhaps some modest enhancement of ozone within the Carson Valley. Most notably, smoke from basin fires has a high potential of affecting the Carson Valley, with impacts on $PM_{2.5}$ mass and degradation of visibility.

Pollutant Sources and Transport

The three major sources of air pollutants within the Sierra Nevada are forest smoke (wildfires, prescribed natural fires, controlled burns), urban sources (again mainly smoke, some vehicular), and the partially or completely desiccated Mono Lake and Owens Lake (alkaline/saline dusts). The urban sources contribute little to total emissions (tons/year), and their high winter concentrations are mainly due to severely limited dispersion; thus there is no theoretical or empirical evidence that their influence is much more than local. The other two sources, however, are large enough that their influence is well documented. The impact of Sierran forest smoke on the Central Valley of California has been mentioned earlier, a consequence of nighttime downslope winds that may be especially important in fall due to decreased ventilation in the valleys, which increases the residence time of smoke, combined with prescribed natural fires and controlled burns in the mountains. However, this is also a period in which agricultural acreage is burned in the valleys, amounting to many hundreds of thousands of acres each fall. Renewed interest in the impact of these Sierra Nevada sources on air quality downwind (east) of the range is partially a consequence of the activities of the Grand Canyon Commission, charged under the Clean Air Act amendments of 1990 to evaluate all sources of visibility reduction in that area. The commission's task groups are aware of plans to increase burning in forested areas and is looking at such sources as the Sierra Nevada.

Data from the Sierra Nevada can place this evaluation in perspective. The results at Lake Tahoe show efficient transport of smoke aerosols (and other components, such as ozone) from the California Central Valley into the Tahoe basin, across passes at roughly 7,000 feet and around mountains that rise to 10,000 feet. This occurs during much of each spring, summer, and early fall. These pollutants certainly influence the Great Basin air quality, although levels are modest. The results of the Cleveland fire of 1992 show massive transport of smoke downwind of the range, but such events are infrequent. Conversely, the valley to mountain transects in Sequoia National Park, 1987, show a sharp reduction in ozone and aerosols between Giant Forest at 6,000 feet and Emerald lake at 10,000 feet. The Emerald Lake site is west of the Great Western Divide, and the peaks to the east of it rise to over 14,000 feet. This supports a very limited pollutant transport efficiency over the mountains to downwind sites in the central and southern Sierra Nevada, both for local forest smoke and valley smoke. Finally, there is well-documented transport across Tehachapi Pass into the Mojave Desert (Pitchford et al. 1984), where elevations decline to around 4,000 feet. As temperatures drop each fall, mountain transport processes weaken and smoke of all kinds tends to stay in the Central Valley. This was certainly the experience in the dry fall of 1995, when smoke from the Sequoia National Park prescribed fires drifted downslope into the valley. In summary, fires that burn under summertime conditions contribute smoke downwind of the range, while spring and fall fires tend to have greatly reduced transport east of the mountains and, conversely, have the greatest local impact. The wintertime inversions in the Central Valley and lack of fires in the Sierra Nevada indicate little Sierra Nevada influence at downwind sites.

A final piece of evidence concerning transport into the intermountain area can be gathered by comparing aerosols at Bliss State Park, Lake Tahoe, with the Great Basin and Grand Canyon national parks. The characteristic signatures of wood smoke are, in order of uniqueness, excess fine potassium (K-non), organic carbon from carbon (C) and hydrogen (H), optical absorption, and elemental carbon. The mean values for each are as follows (IMPROVE 1995):

	Bliss State Park	**Great Basin**	**Grand Canyon**
K-non	8.77 ng/m^3	6.70 ng/m^3	7.83 ng/m^3
C	1.12 $\mu g/m^3$	0.79 $\mu g/m^3$	0.63 $\mu g/m^3$
H	1.17 $\mu g/m^3$	1.01 $\mu g/m^3$	0.87 $\mu g/m^3$
Optical absorption	5.42 Mm^{-1}	4.18 Mm^{-1}	4.26 Mm^{-1}
Elemental carbon	0.15 $\mu g/m^3$ (?)	0.12 $\mu g/m^3$ (?)	0.09 $\mu g/m^3$ (?)

The (?) indicates values close to the detectable limit and thus are statistically weak.

These data show no convincing evidence that there is major transport from the Sierra Nevada into the Great Basin region or the Grand Canyon National Park, because such long distance transport would cause values to decrease as particles are lost during transit. Moreover, because the highest values at Bliss occur in summer and come from the Sacramento Valley floor, a better case can be made for the impact of agricultural burning in California on air quality in the Great Basin region.

Summary

In order to fully characterize the air quality impacts on downwind sites, some additional information is necessary. For instance, a comparison of Carson Valley air quality to data from the east shore of Lake Tahoe, South Lake Tahoe, and Incline would help link pollutant emission in the basin to measured quantities downwind from the basin. Potentially, measurements of pollutants along the transport corridor (Highway 50 over Spooner Summit) would answer questions regarding transport of pollutants out of the basin. The most apparent potential impact, smoke from prescribed fire or wildfire, should have obvious links to sources within the basin. Indeed, anecdotal evidence would indicate that fires within the basin readily affect downwind sites within the Carson Valley. Future research into the impact of prescribed fire smoke on these downwind sites, especially in light of potential increased burning, is warranted.

Issue 3: The Need to Determine the Adequacy of Existing Air Quality Standards to Protect the Tahoe Watershed's Terrestrial and Aquatic Resources through Existing Air Quality Control Programs

With contributions from Tony VanCuren

Responsibility for managing air quality in the Lake Tahoe basin is divided among several agencies at the federal, state, and local levels. Authority to control air pollutant emissions is similarly spread across all three levels of government. With the exception of visibility, the applicable air quality standards (and the pollution control programs that derive from them) are designed to protect public health. Ecosystem protection has not been a major concern in setting these standards, and attaining the specified air quality in the Tahoe watershed, while it may limit the frequency and severity of ecosystem effects due to air pollution, will not guarantee protection of the basin's terrestrial and aquatic resources. This is especially true for long-term cumulative ecosystem damage due to sustained low-level pollution.

What is the present structure of air quality management in the Lake Tahoe basin, and what are the applicable air quality standards?

The baseline air quality standards for the region are the National Ambient Air Quality Standards (NAAQS) established by the USEPA. The NAAQS cover the federally designated criteria pollutants: Ozone (O_3), PM_{10}, CO, NO_2, lead (Pb), and sulfur dioxide (SO_2). On May 14, 1999, the federal 8-hour ozone and $PM_{2.5}$ standards were invalidated in a decision by the US Court of Appeals for the District of Columbia. Enforcement of these standards is in abeyance pending an appeal and final disposition of that case.

California has adopted more stringent standards for the same criteria pollutants, as well as additional standards for sulfates, hydrogen sulfide (H_2S), and visibility-reducing particles (VRP). The state standards include special provisions for even lower permissible levels of CO and VRP for the state-designated Lake Tahoe Air Basin (LTAB), which encompasses the California portion of the Tahoe basin. At this time, the LTAB is classified as in "attainment" of these state standards, with the exception of the VRP standard, for which it is officially "unclassified" due to a lack of monitoring data using the measurement method set by California to determine compliance with the standard. Nevada also has adopted more stringent standards applicable in the Tahoe basin, matching the California LTAB standards for CO and visibility and cutting the 1-hour maximum ozone standard to equal California's statewide standard.

Under the federally chartered bi-state compact that created the TRPA, the authority to determine environmental thresholds to protect various resources was granted to TRPA. TRPA's

thresholds for visibility and CO are essentially the same as the California and Nevada state standards. The applicable air quality standards for the basin are summarized in Table 3-5. In addition to these fixed standards, the recently finalized federal Regional Haze program (USEPA 1999) requires states to determine the sources of anthropogenic visibility impairment at federal Class I areas (such as national parks and wilderness areas) and to develop long-term strategies to improve visibility in those areas. The first long-term strategy will cover 10 to 15 years, and will be reassessed and revised in 2018 and every 10 years thereafter. Under certain circumstances, the regulations allow until 2064 for a state to attain the goal. While these air quality goals cannot be known as of this writing, they may function as an additional set of de facto air quality standards tailored to individual Class I areas. While such goals may eventually put tighter restrictions on air quality in the Tahoe basin, the long lead time for the Regional Haze Program means that, for the near future, the existing standards will control air quality planning and regulatory activity.

At present, the Lake Tahoe area is classified as being in attainment or "unclassified" for all applicable standards except the 24-hour criterion of the California standard for PM_{10}, for which it is designated as being in non-attainment. The Lake

Table 3-5—Air quality standards relevant to the Lake Tahoe watershed.

Pollutant	Federal	California	Nevada
Ozone			
1-Hour Avg.	0.12 ppm	0.09 ppm* (not to exceed)	0.10 ppm
8-Hour Avg.**	0.08 ppm		
Respirable Particulate Matter (PM_{10})			
Annual Mean	50 μg/m³ (Arithmetic)	30 μg/m³ (Geometric)	
24-Hour Avg.	150 μg/m³	50 μg/m³	
Fine Particulate Matter ($PM_{2.5}$)**			
Annual Mean	15 μg/m³ (Arithmetic)		
24-Hour Avg.	65 μg/m³		
Carbon Monoxide			
1-Hour Avg.	20 ppm		
8-Hour Avg.	9.0 ppm	6.0 ppm (LTAB only)	6.0 ppm (above 5,000' MSL)
Nitrogen Dioxide			
Annual Mean	0.053 ppm (Arithmetic)		
1-Hour Avg.		0.25 ppm	
Visibility – Reducing Particles			
10:00 – 18:00 PST (RH<70%)		0.07/km (B_p)	
Visual Range			
Single Observation or Photograph (RH<70%)		30 mi.	

* California's "not to exceed" criterion is equal to Nevada's "not to equal or exceed."
** On May 14, 1999, the federal 8-hr ozone and PM2.5 standards were invalidated in a decision by the US Court of Appeals for the District of Columbia; enforcement of these standards is in abeyance pending an appeal and final disposition of that case.

Tahoe basin currently complies with all valid NAAQS and the invalidated 8-hour ozone standard, but likely would be classified as being in nonattainment for the annual average criterion of the invalidated federal $PM_{2.5}$ standard.

How is air quality regulated in the Lake Tahoe watershed?

Air quality measurement in the basin is divided among political subdivisions and agencies. CARB conducts routine public health-based air quality monitoring at two sites on the south end of the lake, one in central South Lake Tahoe, the other just west of the casinos at Stateline. CARB proposes to add $PM_{2.5}$ at the South Lake Tahoe site, while the Stateline site is scheduled to close. Although monitoring was discontinued at Tahoe City in 1996, CARB plans to establish a $PM_{2.5}$ monitoring site there in the near future. In addition, a new research monitoring site is planned for the Echo Summit area. Historically, the CARB monitoring has focused on locally generated PM_{10} and CO from motor vehicles, and that is expected to continue. The NDEP Bureau of Air Quality (BAQ) operates public health-based monitoring sites at Incline Village and at Stateline just east of the casinos; these, too, focus on PM_{10} and CO. TRPA operates two visibility monitoring sites in the basin, one on the south shore within the urbanized area of South Lake Tahoe, and the other at an elevated unpopulated site in Bliss State Park, just north of Emerald Bay. Data from these sites are being compiled into a long-term record of regional (Bliss) and local (South Lake Tahoe) fine particle mass and chemistry and are documenting visibility impairment in the basin.

In addition to the current monitoring activity in the basin, the federal IMPROVE program may become a permanent source of monitoring data for the unpopulated upland portions of the basin. California has proposed that the Bliss site be adopted as a regionally representative site in the IMPROVE network. As an IMPROVE site, Bliss would represent air quality in wilderness areas on the Sierra crest, including the Desolation and Mokelumne wilderness areas.

There have been and will continue to be a wide range of short-term special purpose monitoring programs in or near the Tahoe basin. The scope of these programs has ranged from seasonal measurements of “acid rain” accumulations to detailed microscale studies of pollutants in and around specific point sources, such as fires and cars. These special studies, some of which are discussed elsewhere in this report, have provided the details needed to put long-term monitoring in perspective and to illuminate the processes that govern the generation, transport, and eventual fate of air pollution in the Lake Tahoe watershed.

All states are required to show compliance with the NAAQS or to develop control plans designed to achieve compliance with them. The rules and policies developed under these plans are codified in federally enforceable State Implementation Plans (SIPs) that are submitted to the USEPA for approval. Under federal law, states are responsible for controlling stationary pollution sources and for insuring maintenance of motor vehicle pollution control devices. New car emission controls are set by the USEPA. California enjoys special status with regard to its ability to set standards for new motor vehicles, in recognition of the unique pollution problems in southern California.

California law delegates air pollution control authority to local air pollution control districts, primarily based on county boundaries. In the Lake Tahoe basin, the basic control responsibility for permitting stationary sources is held by El Dorado and Placer counties.

Nevada holds control at the state level, except for delegation to its two most populated counties, Washoe (Reno area) and Clark (Las Vegas). In the Lake Tahoe basin, Nevada permitting authority is thus split between Washoe County and the state (acting in Carson City and Douglas County).

Under the federal Clean Air Act, primary air quality planning authority is vested in the states. In California, CARB acts as an intermediary between the local air quality agencies and the USEPA. Along with its authority to set environmental thresholds, TRPA has been granted a role in managing air quality through its transportation and land use management authority. Under this structure, El Dorado and Placer counties, in consultation with

TRPA, jointly develop a plan for the LTAB; that plan then is subject to CARB and USEPA approval. In Nevada, TRPA cooperates directly with the state and Washoe County as the state develops its plans.

Will air quality improve, degrade, or remain unchanged under the present regulatory structure?

Emission Growth Potential and Regulatory Responses

The four major categories of air pollutant emissions in the Tahoe region are motor vehicle exhaust, residential wood combustion, road dust, and open burning (wildfires and prescribed fires). Of these, residential wood combustion and road dust are tightly linked to population size.

Wood Smoke

Residential wood combustion has historically been used to track population in the Tahoe area because wood was both less expensive and more reliable than propane and electricity. Over the past decade, natural gas service has been extended to a significant fraction of the basin. However, wood remains the fuel of choice in low-density and low income areas due to lack of alternatives, and it is preferred for its "charm" by many basin residents and visitors, even in areas served by natural gas. TRPA regulations requiring low-emission wood heaters and limiting the number of fireplaces and wood-fired appliances in new construction should reduce the rate of growth of wood smoke emissions, but these regulations alone are unlikely to reverse trends. Public awareness campaigns and "don't light tonight" strategies have proven useful in many urban areas to address occasional severe smoke impacts. However, such a program is of limited value in dealing with the daily smoke burden in the Tahoe basin because the fall and winter nighttime inversions are so persistent that almost every night could be a "don't light" night. In sum, chimney smoke is likely to grow slowly in future years, even if a program is implemented to reduce peak concentrations.

Wild and Prescribed Fire

Wildfire smoke in the Tahoe region is a relatively rare event, thanks to the efficiency of local fire departments, USDA Forest Service, and California and Nevada forestry crews. However, this efficiency has led to an accumulation of standing vegetation that creates both a growing potential for a truly large, catastrophic wildfire and a need for increased prescribed fire in the basin simply for fuel management for public safety. The current prescribed fire goal of the USFS's Lake Tahoe Basin Management Unit (LTBMU) of 2,000 acres of prescribed fire per year represents a significant increase over previous decades, and its air quality impacts have yet to be fully evaluated.

The actual potential for future forestry smoke emissions and the consequent impact on air quality is unclear. At present, the states and forest managers are negotiating a system of policies and practices for "smoke management," which is intended to balance the competing goals of forest management for fuel reduction and ecosystem health, and air quality protection for public health and visibility. The main thrust of this initiative is to control the direction of smoke drift to mitigate impacts on populated areas. At present, there are only limited data available on the emission potential of various types of fires and the efficacy of smoke management to modify emissions, so quantitative predictions of the effects of the planned prescribed fire programs are not available.

The LTAM, described elsewhere in this chapter, exists, in part, to provide a means to assess such issues. However, the model's full value as an aid to planning and decision-making depends not only on additional model development but also on additional field measurements to better characterize emissions and smoke behavior in the Lake Tahoe basin.

Motor Vehicles

Motor vehicle tailpipe emissions have not exhibited a good correlation with population growth due the counteracting effects of recent, more effective automotive emission control systems, especially the effects of improved catalytic converters, electronic fuel injection, and reformulation of gasoline (USEPA 1998). Over the last several years there has been a flat to slight downward trend in measured CO concentrations at South Lake Tahoe and Incline Village, and a sharp

drop at stations near Stateline. The decline in the Stateline area has eliminated measured exceedances of the federal CO standard, so that by 1998 both California and Nevada asked USEPA to reclassify both sites to attainment for CO (NDEP 1998; CARB 1999). Progress in reducing vehicular NO_x emissions has been less dramatic, with improved emission control roughly keeping pace with growth, such that NO_2 measured at Incline Village shows no upward or downward trend over the last several years (NDEP 1998).

Road Dust

Road dust is not a large factor basin-wide, but it can be a significant contributor to PM_{10} at certain times and places, especially along unpaved roads or road shoulders in summer and in areas of heavy traffic where sand is applied to assist traction in winter. This source is not well characterized in the basin at this time, but its growth potential is clearly related to traffic and population. Slow to moderate growth of these emissions is likely outside of the urbanized areas, while congestion and local "housekeeping" measures are expected to keep these at current levels in the densely populated areas.

How would the regulatory system respond to emission increases in the Tahoe basin?

The driving force in air quality regulation is the determination of attainment status for each pollutant for which there is an air quality standard. When standards are not violated, no new emission controls are required. This leaves open the possibility that emissions can grow and air quality can degrade until such time as standards are violated and a formal determination of nonattainment is made.

Population-related emissions in the basin are roughly proportional to total population, but peak concentrations are related to local population density. Therefore, it is possible that considerable emissions growth can occur without triggering new exceedances of the standards. For activity- or policy-driven emissions, such as prescribed fire smoke, the infrequent and spatially dispersed nature of emissions and the intentional policy of preventing smoke intrusions into population centers combine to minimize the potential for these emissions to reach the existing monitoring sites. This suggests that large emission increases could occur and that local pollutant concentrations could exceed the state and federal standards, all without the official monitoring sites measuring exceedances of the standards. Once a decision is made to act, the controls that are implemented will reflect the policies and laws governing the regulatory agency whose standards have been exceeded.

NAAQS Attainment and Future Air Quality under Federal Law

No currently applicable NAAQS are being violated in the Lake Tahoe region, so there is no immediate federal impetus for more stringent emission controls.

The federal policy of Prevention of Significant Deterioration (PSD) exists to prevent emissions growth in attainment areas, but it is unlikely to contain emissions growth in the Lake Tahoe region because it applies only to large industrial facilities. Three federal programs have the potential to limit emissions growth in the basin, depending on future legal, administrative, and political actions. These are the re-establishment of the NAAQS for 8-hour ozone exposure, reestablishment of the annual and 24-hour NAAQS for $PM_{2.5}$, and the implementation of the federal Regional Haze Rule for Nevada and California.

If reinstated, the 8-hour average ozone NAAQS of 0.08 ppm probably would not be exceeded in the basin. Monitoring data from South Lake Tahoe, Stateline, and Incline Village show maximum 1-hour concentrations in the range of .07 to .09 ppm in recent years (NDEP 1998; CARB 1999), and 8-hour calculations for South Lake Tahoe for 1997-1998 range from .066 to .075 ppm (CARB 1999). Because a considerable fraction of the ozone in the basin is transported from the upwind population centers of the San Francisco Bay Area and Sacramento Valley, it is unlikely that, even if exceedances were recorded, control efforts would focus on local Tahoe basin sources of ozone precursor emissions.

The $PM_{2.5}$ NAAQS, if reinstated, would limit both 24-hour and annual average concentration. The 24-hour $PM_{2.5}$ concentration limit of 65 $\mu g/m^3$ is only slightly above the peak mid-winter concentrations for PM_{10} measured at South Lake Tahoe in recent years (CARB 1999). Because the bulk of the PM_{10} in winter is wood smoke, which is well within the size range of $PM_{2.5}$, it is possible that this standard could effectively cap particulate emissions in this area at roughly current levels.

The annual average $PM_{2.5}$ concentration limit, 15 $\mu g/m^3$, is well below the annual average PM_{10} concentrations in South Lake Tahoe (ranging from 19 to 23 $\mu g/m^3$ in recent years) and Stateline (18 to 27 $\mu g/m^3$ over the last decade), and close to the values for Incline Village (15 to 18 $\mu g/m^3$ in recent years) (CARB 1999; NDEP 1998). While these numbers include data from summer, when PM_{10} is a combination of $PM_{2.5}$ and coarser material, if is possible that the annual average standard already is exceeded along the south shore. If this standard were reinstated, a chimney smoke reduction program requiring a roughly 25 percent emission reduction probably would be required on the south shore and chimney smoke emission growth would be prevented in other populated areas of the basin.

The federal Regional Haze Program requires states to develop plans to return to natural visibility conditions in Class I areas (in the Tahoe region, this means Desolation Wilderness). Unlike a standard, the haze rule requires a state to adhere to the following:

"Analyze and determine the rate of progress needed to attain natural visibility conditions by the year 2064. To calculate this rate of progress, the State must compare baseline visibility conditions to natural visibility conditions in the mandatory Federal Class I area and determine the uniform rate of visibility improvement . . . to attain natural visibility conditions by 2064." (USEPA 1999)

The effect of this program on the long-term allowable emissions in the Lake Tahoe region is unclear at this time. Preliminary analyses of data from TRPA's visibility monitoring program indicate that there is only a weak connection between air quality at lake level and that on the ridgelines around the lake. Because Desolation Wilderness is usually upwind of the basin, it is likely that any plans developed to return "natural" visibility conditions to Desolation Wilderness would focus on upwind areas to the west and could involve little or no emission reductions in the populated areas of the basin. More problematic is the question of the impact of the regional haze rules on prescribed fire emissions. Evolving federal policy suggests that at least some prescribed fire smoke would be allowed as a "natural" emission in wilderness areas, but the manner in which this distinction would be drawn is unknown at this time (WESTAR 1995).

State Standards

Unlike federal standards, standards in California and Nevada are not linked to automatic triggers for new emission control programs, nor are there mandated time frames to achieve compliance. When and if state standards are violated, it is incumbent on local agencies, such as counties and TRPA, to initiate efforts to impose additional controls or to ask the states to impose controls. Historically, such local actions have been limited or nonexistent outside the Tahoe basin, so it is difficult to predict the speed and scale of state responses to new or continuing evidence of violations of state standards.

CO standards conforming to the threshold set by TRPA (6 ppm, 8-hour average) have been adopted by both California and Nevada. Monitoring data from South Lake Tahoe and the CARB Stateline site show maxima of 2.4 and 4.3 ppm, respectively. The Stateline data show a downward trend, with no values in excess of 5 ppm since 1990 and current values ranging from 2.1 to 2.8 ppm. Incline Village data show a similar trend, with recent values ranging from 1.6 to 2.5 ppm (CARB 1999; NDEP 1998). At this time there is no reason to expect any automotive emission reduction efforts in the basin aimed at reducing CO.

Ozone standards more stringent than the NAAQS also have been adopted by California and Nevada (California: "not to exceed .09 ppm"; Nevada "not to equal or exceed .10 ppm"). Monitoring data from South Lake Tahoe, Stateline, and Incline Village show maximum 1-hour concentrations in the range of .07 to .09 ppm in

recent years (NDEP 1998; CARB 1999). Although these are close to the allowable limits, neither state has expressed any concern that they will be exceeded in the near future. Because a considerable fraction of the ozone in the basin is transported from the upwind metropolitan areas, it is unlikely that, even if exceedances were recorded, control efforts would focus on local Tahoe basin sources of ozone precursor emissions.

Visibility standards adopted by California and Nevada provide protection for the Tahoe basin at a level roughly equivalent to a visual range of 30 miles. The monitoring being conducted by TRPA indicates that the standard is violated infrequently in remote upland areas of the basin and that it is regularly violated in densely populated areas such as South Lake Tahoe, where visibility often drops below 20 miles. Although both states are aware of these conditions, lack of routine monitoring in a form compatible with state standards has prevented either state from formally declaring the basin as being in nonattainment for visibility.

TRPA Thresholds

The TRPA thresholds for gaseous pollutants are not being violated at this time, but the subregional and regional thresholds for smoke and visibility are being exceeded. Fine particle ($PM_{2.5}$) concentrations must be reduced by 25 percent basin-wide and 65 percent in South Lake Tahoe to attain the "basin carrying capacity" visibility goal set by TRPA in 1981 (Molenar et al. 1994).

TRPA does not have direct emission control authority, so no immediate regulatory actions are forthcoming. TRPA can respond to these violations by pursuing further reductions in new source construction (fireplaces and wood-fired appliances) and in working with the state and local air pollution agencies to develop additional measures to reduce wood smoke.

Are the present standards and programs adequate to prevent adverse effects on the scenic, terrestrial, and aquatic resources in the basin?

The various air quality standards discussed above derive from legal authority to protect public health and welfare (enjoyment of the environment). The extent to which they provide protection for other resources is serendipitous, and there is no assurance that these standards will be retained or strengthened on the basis of such benefits. The following discussion explains why current air quality standards and their associated pollution control programs do not fully protect the nonhuman resources in the Tahoe basin.

Scenic Resources

The scenic resources of the Tahoe basin are among its most important attractions for both residents and visitors. Any degradation of visibility detracts from the social and economic value of the Tahoe basin. The current regulatory structure explicitly recognizes the importance of visibility in the basin through the state visibility standards and the TRPA regional and subregional thresholds. These standards were tailored for the Tahoe basin and as such are presumed to be appropriate to protect the basin's scenic quality. If further study indicates that the protection is inadequate, TRPA has the mandate to reconsider the standard levels with the explicit goal of protecting visibility in the Tahoe basin.

Terrestrial Resources

"Terrestrial resources" are intended to include the soil, plants, and animals of the Lake Tahoe basin. While not all elements of the terrestrial ecosystems in the basin have been studied for their sensitivity to air pollution, many are known to be sensitive to the direct phytotoxic effects of ozone and sulfur dioxide. Secondarily, there is a potential for natural nutrient cycles to be disrupted due to deposition of acids, primarily nitric acid derived from NO_x emissions.

There do not appear to be sufficient sources of SO_2 in the Tahoe region to directly threaten terrestrial vegetation or wildlife. Ozone, however, is known to cause some visible vegetation damage in the basin. Studies of ozone damage in other areas of California indicate that the current damage levels are modest and may not pose any immediate threat to the health of Tahoe's forests. However, a critical review of ozone injury data compiled by CARB (CARB 1987) concluded that, because vegetation injury is due to growing-season

accumulated dose, short-term health-based ozone standards may reduce the frequency and severity of plant damage, but they do not fully protect against it, It is reasonable therefore, to conclude that the present ozone damage in the basin will persist unabated under current air quality standards. In fact, CARB's review suggests that, even if the federal 8-hour standard is reinstated, some vegetation injury would be allowed under the standard.

While ozone concentrations in the Tahoe basin appear to be stable, and they are well below levels found in urban California, they are still far above natural concentrations. A general consensus is emerging that average daily peak summer ozone levels at pristine, mid-northern latitude sites are about 0.03 to 0.04 ppm, based on remote site measurements, such as those taken at NOAA's Mauna Loa Observatory in Hawaii. Because summer ozone levels in the northern Sacramento Valley, where anthropogenic influences are modest, approach those levels today (0.059 ppm in Redding, 0.052 ppm in Chico), preindustrial ozone levels in the central and southern Sacramento Valley can be estimated as being somewhere between 0.035 and 0.05 ppm. Present summer ozone concentrations in the San Joaquin Valley and southern Sacramento Valley regularly double or triple these preindustrial levels. Because these areas are the sources of air advected into the Sierra Nevada, it is reasonable to conclude that the entire west slope of the range is experiencing ozone concentrations well above natural levels.

Acid deposition also may harm vegetation at low levels through a synergistic heightening of sensitivity to ozone and at high levels by direct injury. Present data suggest the damage is minimal, if any, in the Tahoe basin (CARB 1989). The major precursor pollutant for acid deposition in California is NO_x. Because NO_x control is a major element of California's ozone control program, continued efforts to control ozone in the upwind cities and to reduce vehicular NO_x statewide probably will prevent any increase in deposition from transported pollutants and limit or prevent the growth of nitric acid deposition from locally emitted NO_x in the Tahoe basin.

Soil resources consist of both biotic communities and mineral and organic nutrients stored in the soil. Air pollution can threaten soil when wet- and dry-deposited acids accumulate and when acids are released during spring snowmelt. Acidity alone can change the pH of the soil water, increasing the solubility of certain ions and promoting leaching. Mobilized ions also may damage roots and soil biota, while the acid ions themselves (especially nitrogenous species) can act as fertilizers, upsetting the nutrient balance in the soil. As with direct vegetation injury, CARB has determined that current acid deposition rates are not sufficient to pose significant short-term risk to soils, and large increases in deposition in the future seem unlikely (CARB 1989).

Aquatic Resources

Air pollution damages aquatic resources in the Tahoe basin by fertilizing surface waters, which promotes algal growth and consequent loss of lake clarity. Principal sources of these excess nutrients are nitrates and nitric acid derived from NO_x emissions and phosphorous from wood smoke. The exact pathways by which these pollutants reach the lake are not fully known, but it is likely that the pathways are both direct through deposition to water surfaces and indirect deposition via accumulation in snow with later release during spring melt.

A secondary pathway for air pollution to affect the Tahoe watershed's aquatic resources is by acid deposition, both direct and indirect. CARB's measurements of acid inputs in the Sierra (CARB 1989) show that precipitation in the South Lake Tahoe area has about 50 percent higher concentrations of acidic species than are found in less populated sites in the northern Sierra, such as Norden and Quincy. The reduced total precipitation at lake level, however, results in a net input of about half the annual flux of acidic species that is seen at Norden on the Sierra crest. To put the anthropogenic acidic impact in urbanized South Lake Tahoe in perspective, it is not large enough to produce any direct acidic impacts and is less than one third of the impact observed on the western slopes of Sequoia National Park, with its open

exposure to the San Joaquin Valley. Nonetheless, it should not be ignored as a potential pathway for airborne material to be collected and delivered to Lake Tahoe.

Overall there remain several areas of significant uncertainty regarding the timing, volume, and pathways of deposition to the lake, and additional work is needed to properly measure deposition fluxes (Jassby et al. 1994).

Issue 4: The Need to Assess the Relative Impact of Air Quality Sources to Other Sources in Lake Tahoe Basin Welfare

The commitment to maintain or to reestablish levels of ecosystem health at Lake Tahoe that are commensurate with health and welfare requirements must be directed intelligently in order to obtain the greatest possible benefit from the resources committed. This will require an appreciation of the relative role of air quality in degrading the ecosystem compared to other inputs from terrestrial and aquatic sources. The specific questions listed below summarize the more detailed information included in Issue 1, namely the requirement for a Lake Tahoe basin air model (LTAM). Issue 1 includes numerous tables and figures that support the conclusions summarized below. The information on terrestrial and aquatic inputs must come from other sections of the report, and thus a definitive answer must await a combination of the individual components of this report.

What are the relative impacts of transported versus local nitrogenous air pollutants on lake clarity?

The answer to this question requires information on the following independent factors, each of which has important areas of uncertainty:

1. What are sources of nitrogen in gaseous and particulate form over Lake Tahoe itself and over the surrounding terrain?
2. What are the concentrations of nitrogenous pollutants, gaseous and particulate, above the lake surface and surrounding terrain?
3. With what efficiency do these materials enter the lake, either directly by wet or dry deposition into the lake surface, or indirectly via runoff?
4. What is the impact of nitrogen in reducing lake clarity?

In reference to local versus transported sources on nitrogen, the location of the sources of particulate nitrates largely has been resolved. During spring, summer, and fall most particulate nitrate is transported from upwind sources. In winter, the particulate nitrate is local in origin, with heavy transportation sources but also including other forms of combustion. During all times, gaseous nitrogen, NO_X, is of local motor vehicle origin (Cahill et al. 1977). The distribution of gaseous nitrogen (NO and NO_2, which generally sum to NO_x) away from the single current CARB measurement point at South Lake Tahoe is derived in the LTAM model by using the 1973 CARB measurements, past and present traffic, relative emission rates, and NO_x trend data. LTAM then predicts concentrations of gaseous species over the lake and surrounding terrain.

The particulate nitrogen is in the form of ammonium nitrate, which in spring, summer, and fall is transported into the basin from upwind urban sources in the Bay Area, Sacramento Valley, and Sierra foothills. The mean concentrations are roughly 0.3 $\mu g/m^3$. Due to the fine size of the particles and the distance of transport, the values are uniform across the entire Lake Tahoe basin. The winter nitrate from urban areas is typically around 1 $\mu g/m^3$ at South Lake Tahoe but is not adequately characterized for confidently predicting concentration profiles away from the measuring site. Estimates are made from other particles in the LTAM to obtain concentrations over the lake surface near urban sites and the surrounding terrain. The result is that while the concentrations vary in space and time, total nitrogenous compounds in the air above and near the lake are overwhelmingly local in origin.

The rate of wet deposition into Lake Tahoe's surface, mostly as snowfall, is well known and subject to only minor uncertainties. The snow quality above Lake Tahoe is quite clean (Cahill et al. 1996a) and is typical of the near pristine conditions of the southern Cascade Range. Dry deposition into the lake, directly or indirectly, is especially uncertain,

as measurements have yet to connect the excellent long-term deposition record of TRG (Jassby et al. 1994) with the equally solid measurements of airborne nitrogenous compounds (Molenar et al. 1994). We have attempted to resolve these problems in LTAM. From the atmospheric data given above, LTAM makes calculations of dry deposition from the measured nitrate concentrations (Sehmel 1980). A mean transported nitrate concentration of 0.3 $\mu g/m^3$, from the Bliss site but averaged over the entire lake surface, yields deposition values between 0.4 and 1.0 ton/year, well below those inferred from the TRG measurements (Jassby et al. 1994). Adding in the local anthropogenic particulate nitrate, 0.3 $\mu g/m^3$, inferred from the South Lake Tahoe site after subtracting the transported component, assuming a somewhat larger particle size for humid winter conditions and averaging over that portion of the lake near urbanized areas, yields an additional 0.1 to 0.3 tons/year. In contrast, using local gaseous NO_x concentrations from vehicles and the same type of calculations, but this time over a 1-km wide band around the lake, yields a mean NO_x concentration of 22.6 $\mu g/m^3$, roughly 75 times the concentration of transported particulate nitrate. LTAM has performed these estimates over each square mile of the lake surface, showing that the direct deposition of local NO_x gasses always dominates transported particulate nitrates by factors of 10 to 100, depending on location.

Additional uncertainties arise from indirect deposition via inert surfaces at the edge of the lake. If only 10 percent of the NO_x is scavenged onto trees and surfaces to eventually reach the lake in spring snowmelt, this yields on the order of 20 (or more) tons per year into the lake, with a spatial pattern that closely matches observed maxima in algal growth. Since there are major uncertainties in making subsurface nitrate measurements from urban runoff, direct observation of this effect is difficult. Even these factors do not appear to explain the increasing turbidity of Lake Tahoe because NO_x levels have been steadily decreasing over the past 20 years, while lake conditions grow steadily worse. Atmospheric deposition is a major factor in nitrate input to the lake, resulting in a tons per year prediction of nitrate input to the lake. By comparison to the nitrate input from streams and runoff, this gives an atmospheric source that dominates nitrate input to the lake. However, dry deposition measurements are notoriously difficult to do accurately, and questions remain on input pathways of nitrogen (Jassby et al. 1994). Some of the dry deposition nitrates, impacted onto inert surfaces, will enter this lake through snowmelt and runoff, thus fertilizing the lake and contributing to the roughly 30 percent degradation in water quality observed since 1958 (Goldman 1994). Clearly, the question of local versus transported sources becomes critical, as does the ratio of these nutrients to those contributed to runoff from urbanized areas and soil disturbance from development. This is the subject of active investigation at this time and a clear consensus has yet to be achieved.

The effect of these nitrogenous inputs on lake clarity is included in the aquatic section of this report. However, there is some indication that although atmospheric NO_x has been declining over the last 30 years at Tahoe, the algal growth rate continues to increase (Figure 3-34). Because the situation for phosphorous is dramatically different (see next section), Figure 3-34 also shows a correlation between housing increases (as single-family housing units) and algal growth, where soil disturbance may release more phosphorous into the lake during the decline in atmospheric NO_x.

What are the relative impacts of transported versus local phosphate containing air pollutants on lake clarity?

Measurements of phosphate in TRG deposition buckets gives a significant component to all phosphate input into the lake. Yet, little or no phosphate is seen in TRPA aerosol measurements. The most likely conclusion is that the phosphate particles are in the form of large wood ash flakes that would be eliminated from the TRPA aerosol measurements. Some support for this was mentioned in early UCD/TRG aerosol measurements in 1976, before inlet restrictions were used, and in a single experiment in February 1999. Further, unlike the situation with atmospheric nitrogen, a good match is seen when one compares

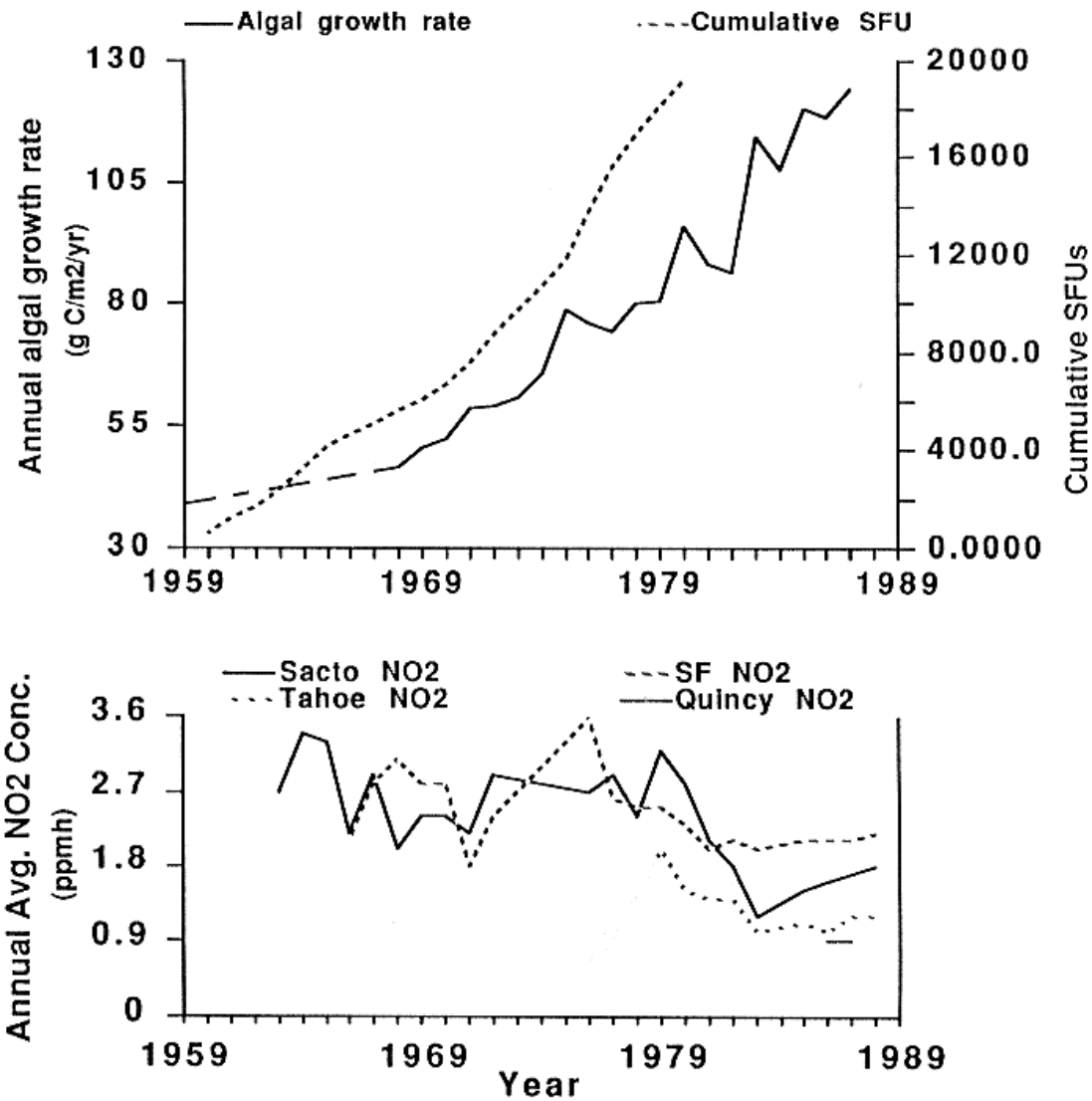


Figure 3-34—Correlation of single-family housing units (SFUs) and algal growth rate at Lake Tahoe (top). Concentration of atmospheric NO_2 for the same period showing steady decline when algal growth is increasing (bottom).

development around the lake, with development's attendant soil disturbance and mobilization of phosphorous, to algal growth. The increase in the levels of wood smoke, with a phosphorus component, and the increase in local traffic resulting in fine roadway dust in which there is a component of phosphate, support this hypothesis. Because these phosphate sources are entirely local, and thus there is essentially no transported contribution to the phosphate deposited into Lake Tahoe from airborne sources. The role of airborne phosphates on lake clarity is discussed in Chapter 4.

How well known are the deposition rates of atmospheric pollutants to Lake Tahoe?

Atmospheric deposition of gasses and particles are poorly known in general, as these rates depend not only on the concentration and, for particles, size, but the rate at which the gasses and

particles are emitted from the surfaces on which they are deposited. As an example, atmospheric nitrogen (N_2) is being continually deposited onto the surface of Lake Tahoe at an enormous rate because this gas makes up roughly 80 percent of the atmosphere. But it is being re-emitted back into the atmosphere at precisely the same rate because it is not retained in the water surface, where N_2 is not soluble to any significant extent. The counter example is that of a large particle, such as coarse soil dust. This has far lower concentrations in the atmosphere and thus lower deposition flux to the surface by a factor of about 100,000 less than N_2, but the re-emission rate is zero, as every particle is captured by a water surface. Coarse soil particles thus have a significant deposition rate, while atmospheric N_2 does not. The combined factors are usually included in a deposition velocity v_d, which for coarse particles with 100 percent retention rate, is just the settling velocity in the air. These are typically 1 to 2 cm./sec. Gasses and very fine particles, $D_p < 0.1$ µm, have about the same deposition velocities from diffusion but have vastly different retention rates. Very fine particles are retained at 100 percent, N_2 is retained at 0 percent, and everything else lies in between.

These considerations are discussed in length in Issue 1, which establishes the need for an atmospheric model. Deposition calculations have been incorporated into the LTAM model but this aspect has not been exercised, and no net deposition rates have been derived at this time. While this is due to a number of factors, including the very short time available to build and validate the model for a vast number of parameters, the most important reason is that the uncertainty of the deposition rates for several important species are so poorly known that calculations based on these rates could be misinterpreted.

In the face of these uncertainties in the atmospheric side of the equation, it is worthwhile to consider closely the deposition measurements of the TRG (Jassby et al. 1994). The TRG deposition collection started using standard wet-dry collectors, but in 1988 switched to a "dry" collector with a layer of water in the bottom. This was done to better mimic the lake deposition process and immediately tripled the collected nitrate. This raised TRG "dry" deposition rates far above those seen by CARB in its dry deposition network. However, no detailed studies were done of this new system against standard systems, such as aerosol collectors, leaving large uncertainties as to what is actually ending up in the "dry" water pool. The presence of a warm water pool in the bucket for the typical week of collection allows for a number of processes absent in standard dry deposition systems, the most important of which is the increased collection of NO_2, which does possess the ability to enter water. Thus, the TRG dry deposition value almost certainly includes some gaseous NO_2, which is then highly relevant to lake deposition processes. But there may be other processes, including bacterial attack on organic nitrate from forest debris, that must be studied and evaluated. Finally, the on-lake deposition measurements are limited in space and time, as this is very difficult work. In particular, there is a lack of deposition measurements near South Lake Tahoe during the periods of strong inversions and strong local sources, leading to high predicted deposition rates.

All of these aspects need additional focused research on exactly what deposition occurs in the conditions of Lake Tahoe in order to achieve closure between atmospheric concentrations, theoretical predictions, and measured deposition rates.

What are the relative impacts of prescribed fire (low temperature) smoke and wildfire (high temperature) smoke to lake clarity?

Coupling atmospheric concentration of pollutants to lake clarity is nearly impossible at this time. Needed are measurements of specific pollutants in air with varying season and conditions and coupled measurements of these pollutants in the water column as a measure of deposition. Furthermore, precise measurements of the source of degraded lake clarity, i.e., fine particles versus algae, are necessary. There is some evidence of algal blooms after wildfires, which makes sense because all three components needed for degrading lake clarity (phosphate, nitrate, and fine particles) are abundant in the smoke of wildfires. Little is known about the effect of prescribed fire and lake clarity

from an atmospheric perspective. Measurements of emission from fire sources are sorely needed in the Lake Tahoe basin to accurately predict effects of fires on Lake Tahoe.

Questions of lake clarity are considered in Chapter 4.

What is the nature of smoke from different types of wildfire (ground, passive crown, active crown) and prescribed fire?

Crown fires have a major potential to cause declines in lake clarity due to simultaneous generation of three key contributions to algal growth in Lake Tahoe—nitrates, phosphates, and fine particles. These are greatly reduced in prescribed fires in which temperatures are lower and nitrate rich needles are generally preserved, and the strong vertical lofting of wild fires is absent or greatly reduced. There is evidence of substantial differences in smoke from fire types (Turn et al. 1997) and recent data show nitrate loss from crowning fires that is probably not involved in low temperature ground-based litter burns of prescribed fire. However, measurements of these effects are spotty. The intense nitrate peak seen at the TRPA Bliss site during the 1992 Cleveland fire (active, crowning) supports the theories, as does the lack of a nitrate spike during prescribed fires at Yosemite National Park in 1992 (Cahill et al. 1997). No direct evidence of the phosphate and fine particle contributions have been developed for any of the fire types. This is clearly a key area for immediate research if the smoke from future prescribed fires lingers over Lake Tahoe under the inversion and thus with high deposition potential, according to LTAM.

Issue 5: The Need to Establish the Means by which Emissions Can Be Reduced to Levels Necessary to Avoid Deleterious Effects

The rationale for mitigation efforts is based on the details contained in the answers in this report and the extensive literature referenced, especially Cahill et al. (1996a). In this section we list major opportunities for mitigation, the reasons for these choices, and some indication of the impact of the mitigation. But the answers will direct us to the specific and focused research needed to provide quantitative estimates of mitigation efficacy. Further, efficiency of mitigation will depend on the costs involved, which lies outside of the scope of this report.

Lake Clarity

Since the early 1980s, phosphorus has been the most sensitive addition to enhancing algal growth in Lake Tahoe. The estimates are that airborne phosphorus is about half the total phosphorus input to the lake, yet existing measurements of PM_{10} and $PM_{2.5}$ aerosols indicate only very small (ng/m^3) concentrations in the air above the lake. There are only two options to make these results agree: phosphorus must be depositing in the TRG buckets either from a gaseous form or from particles larger than 10 microns in diameter. Because no source for gaseous phosphorus is known in nonindustrial situations, we must assume as a working hypothesis that there are coarse phosphorus particles present at the TRG deposition sites. Because this is seen even in the middle of the lake, then we must have a coarse particle that does not settle out as rapidly as coarse particles would if they were from typical soils. We are thus led to a large and known phosphorus source at Lake Tahoe, wood fires. Fire ash is large, flaky, and of low density such that it can travel over the lake. Still, it would eventually settle with high efficiency onto the lake, especially because wood smoke is most present in late fall, winter, and spring, when ventilation is often weak over the lake. Assuming that this is the somewhat mysterious source of phosphate seen in the TRG dry deposition buckets, phosphate could be mitigated by screens placed on the chimneys of all open fireplaces and by the use of low emission hardwood fuels and low emission wood stoves. Mitigation should include proper handling of all phosphate-rich wood ash, which we suspect is often just dumped on the ground because putting hot ashes into waste cans is prohibited.

Nitrogen continues to be an important factor in lake eutrophication at Lake Tahoe. Important uncertainties continue to hinder a clear resolution of the relative impacts of airborne and aquatic sources of nitrogen, despite long-term and credible measurements of both airborne and aquatic nitrogen, because the relative importance of nitrogen emission sources to TRG deposition data is still undetermined. Until the importance of nitrogen

emission sources is determined, a firm strategy for mitigation cannot be crafted. Lacking that, the safest approach is to mitigate both components roughly in proportion to their importance and the cost for removal, generally crafted in the metric dollars per ton removed. If the gaseous component derived from local traffic is the major factor, controlling nitrogenous emissions becomes the major component. In this regard, diesels emit far more NO per mile than gasoline-powered cars, especially at high altitude where cars emit less NO than at sea level. Thus, the most efficient strategy is one based on actual emissions, as a small number of vehicles are probably a large fraction of the total emission load. Two possible ways to control the use of diesel in the basin is to limit access to diesel in South Lake Tahoe and to impose a local tax on diesel to support environmental efforts. Of secondary importance, traffic reduction in general is a useful mitigation component and has been used successfully at Lake Tahoe. To see this, the traffic volume has risen very little in the past 20 years, while single-family housing units have more than doubled. Finally, moving traffic away from the lake edge reduces the efficiency of transport from roadways into the lake. As an example, if the Pioneer Trail in South Lake Tahoe were made into Highway 50 and bypassed on the upslope side of the Nevada-California state line, our model predicts sharply reduced lake impact. In addition to the general falloff in transport, deposited nitrogen has a much longer biological filter to traverse before reaching the lake. This also allows an attractive "Old Highway 50" corridor on the lake, ideally supported by light rail.

If the dominant nitrogen sources are particulate nitrogen, most of this material in summer comes across the mountains in the summer wind. In this case, only upwind controls can be effective, a much more daunting task. There is still an important component of local nitrogen-containing particulate matter in winter, tied to both traffic and wood burning. The authors of this chapter lean toward local gaseous pollutants as the most important factor and are pursuing, together with TRG, the definitive measurements that could solve this problem.

Fine soil particles have both a local and transported component, roughly 50-50, with a spring peak in both cases. This is unfortunate because this is exactly the period when algal growth accelerates in the lake. Local sources are unpaved road (much less now than in prior years), dust from roadways each spring as a consequence of winter sanding and spring runoff onto roads, and other sources. Transported sources are largely agricultural in origin, from disturbed soils in the Sacramento Valley.

Air Clarity

Air clarity at Lake Tahoe from roughly 1900 to 1960 was probably considerably better than at any time before or since. The natural fires were greatly reduced or absent because so much of the forest had been clear cut, what wild fires occurred were being extinguished by the USFS, housing and year round residential activities were low, and traffic was modest. The recent situation is summarized well in Molenar et al. (1994), and, unlike water clarity, there are few uncertainties regarding the causes of degradation of air clarity. Mitigation then depends on controlling nitrates, smoke sulfates, and soils in the western slope and Sacramento Valley in summer and local wood burning and nitrogen from cars in winter.

Forest Health

The major source of forest damage is ozone, and the ozone is almost entirely from upwind sources during the period when the trees are vigorously growing. Thus, little can be done within the basin. There would need to be limits for summer vehicular emissions (HC, NO) in the foothill Hwy. 50 and I-80 corridors, especially during afternoons in summer. Traffic in the foothills has greatly increased in the past decade. Mitigation would involve such efforts to decrease the traffic as providing alternatives to the car and supporting car pooling.

Human Health

With the successful mitigation of carbon monoxide from vehicles, fine particles, especially $PM_{2.5}$, now appear to pose the major health impact. Because much of the $PM_{2.5}$ is local and is tied to wood smoke, mitigation efforts could include a switch from wood to gas fireplaces and stoves, EPA-

certified low emission wood stoves, cleaner burning hardwood, such as dried fruit wood for existing open fireplaces, and scheduled burn-no burn days in the basin tied to inversions.

These mitigation efforts will be listed roughly in order of the seriousness of the impacts, with the continuing decline in lake clarity driving much of the present concern and research at Lake Tahoe.

Potential Mitigation Strategies for Reducing Airborne Inputs to Lake Tahoe

The strategies listed below each attempt to lower the key components that affect the Lake Tahoe basin. However, without consideration of the cost-benefit analysis essential for intelligent planning, they must be considered merely as a starting point for more complete analyses.

Impact	Key Factor	Potential Controls
Lake clarity	Phosphorous	Control ash effluent from fire places by using chimney screens and EPA-certified stoves, use hardwood fuels, control phosphate-rich ash disposal, reduce roadway dust (see below), prevent wildfires.
	Nitrogen	Control winter nitrates by restricting wood burning, traffic controls (especially on diesels) for NO_x reduction, reduce traffic near lake edge by controlling vehicular flows and moving traffic away to interior roads (e.g., Hwy. 50 to Pioneer trail), prevent wildfires.
	Fine dust	Control condition of roadways (especially in spring), ban leaf and dust blowers, reduce traffic near lake edge by controlling vehicular flows and moving traffic away to interior roads (e.g., Hwy. 50 to Pioneer trail), prevent wildfires.
Air clarity	Local smoke	Limit all types of burning in the Tahoe basin in fall, winter, and early spring conditions of low ventilation; in winter, limit wood smoke from stoves, vehicle exhaust smoke (especially diesels), limit prescribed fire to periods of good ventilation and dry fuel, especially summer, limit smoke from upwind (western slope of the Sierra) in summer, good ventilation conditions.
Regional haze	Sulfates, nitrates, smoke	Control sulfates from Bay Area oil refineries, control nitrates from the Sacramento Valley and Bay Area, reduce agricultural smoke in the Sacramento Valley, limit smoke from prescribed fires on the western slopes of the Sierra Nevada in summer transport conditions.
Forest health	Ozone	Limit summer vehicular emissions (HC, NO) in the foothill Hwy. 50 and I-80 corridors, especially afternoons in summer.
Human health	Fine particles/smoke	Control wood stoves in winter, avoid prescribed fire during inversion conditions (especially fall).

References

Beaton, S. P., et al. 1995. On-Road Vehicle Emissions: Regulations, Costs, and Benefits. Science 268: 991-993.

Bohm, M., B. McCune, T. Vandetta. 1995. Ozone Regimes in or near Forests of the Western United States: Part 2. Factors Influencing Regional Patterns, J. Air and Waste Management Assoc. 45, 477-489.

Cahill, T. A., et al. 1989. Monitoring of atmospheric particles and ozone in Sequoia National Park: 1985- 1987. Final report on contract A5-180-32, California Air Resources Board, Sacramento.

_____. 1995. Saltating particles, playa crusts and dust aerosols from Owens (Dry) Lake, California. Earth Surface Processes and Landforms. In press.

_____. 1997. Sierra-Nevada Ecosystem Project. Chapter 48.

Cahill, T. A., J. J. Carroll, D. Campbell, and T. E. Gill. 1996a. Air Quality. *In:* Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II, Chapter 48. Davis: University of California, Centers for Water and wildland Resources.

_____. 1996b. Air Quality. *In:* Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. III, Chapter 21. Davis: University of California, Centers for Water and wildland Resources.

Cahill, T. A., L. Ashbaugh, J. Barone. 1977. Sources of Visibility Degradation in the Lake Tahoe Air Basin. California Air Resources Board contract #A-5-005-87.

Cahill, T. A., D. D. Dutcher, Chris Clark, and J. Martin. 1998. Comparison of Cardiac and Stroke Mortality to Carbon Monoxide, Ozone, and Particulate Air Pollutant Concentrations in the Sacramento Valley Region. Report to the American Lung Association of Sacramento. Pp. 31. June 1998.

California Air Resources Board (CARB). 1979-1994. California Air Quality Data. Published quarterly by California Air Resources Board, Sacramento.

_____. 1974. Air Pollution in the Tahoe Basin, Summer 1973. A report from the California Air Resources Board, March 1974. Pp. 26.

_____. 1987. Effects of Ozone on Vegetation and Possible Alternative Ambient Air Quality Standards, Technical Support Document, CARB Research Division. March 1987.

_____. 1989. The Health and Welfare Effects of Acid Deposition in California: Technical Assessment, State of California Air Resources Board. June 1989.

_____. 1999. CARB ADAM On-line Data System, (http://www.arb.ca.gov/adam/welcome.html).

Copeland, Scott. 1995. USDA Forest Service, Fort Collins, Colorado, personal communication (to TAC).

Elliott-Fisk et al. 1997. Lake Tahoe Case Study. Status of the Sierra Nevada Addendum. Sierra Nevada Ecosystem Project Final Report to Congress. *Wildland Resources Center Report No.* 40. University of California, Davis.

Goldman, C. R. 1994. Annual Report of the Tahoe Research Group. University of California, Davis.

IMPROVE 1995: Data Base and Quarterly Summary of Interagency Monitoring of Protected Visual Environments (IMPROVE) 1988-1995. Air Quality Group, University of California at Davis.

Jassby, Alan D., J. Reuter, R. Axler, C. Goldman, and S. Hackley. 1994. Atmospheric deposition of nitrogen and phosphorus in the annual nutrient load of Lake Tahoe (California-Nevada). Water Resources Research, 30(7):2207-2216. July 1994.

Jenkins, B. M., et al. 1993. Atmospheric pollutant emission factors from open burning of agricultural and forest biomass by wind tunnel simulations, final report (draft). CARB Project No. A932-126, California Air Resources Board, Sacramento, California.

Jenkins, B., A. Jones, S. Turn, and R. Williams. 1995. Emissions of polycyclic aromatic hydrocarbons (PAH) from biomass burning. Report presented before the 209th

American Chemical Society Annual Meeting, Anaheim, California. April 1995.

Laird, L. B., H. E. Taylor, and V. C. Kennedy. 1986. Snow Chemistry of the Cascade- Sierra Nevada Mountains. Environmental Science and Technology 20(3): 275- 290.

Larson, T. V., and J. Q. Koenig. 1994. Wood Smoke: Emissions and Noncancer Respiratory Effects. Annual Review of Public Health 15: 133- 156.

Lave, L. B., C. T. Hendrickson, F. C. McMichael. 1995. Environmental Implications of Electric Cars. Science 268: 993-995.

Mahern, Bridget. 1996. Tahoe Regional Planning Agency, Zephyr Cove, Nevada, personal communication (to TAC).

Malm, W. C., J. F. Sisler, D. Huffman, R. A. Eldred, and T. A. Cahill. 1994. Spatial and seasonal trends in particle concentration and optical extinction in the United States, Journal of Geophysical Research, VOL. 99, No. D1, 1347-1370. January 20, 1994.

Marchand, D. E. 1970. Soil contamination in the White Mountains, eastern California. Geological Society of America Bulletin 81(8):2497- 2505.

McGauhey , P. H., R. Eliassen, G. Rohlich, H. F. Ludwig, E. A. Pearson, and Engineering Sciences, Inc. 1963. Comprehensive study on protection of water resources of Lake Tahoe Basin through controlled waste disposal. Prepared for the Lake Tahoe Area Council. San Francisco: Engineering Sciences, Inc.

McKey, M. 1995. Unpublished USDA Forest Service records on the Cleveland Fire.

Molenar, J., D. Dietrich, D. Cismoski, T. Cahill, and P. Wakabayashi. 1994. Aerosols and visibility at Lake Tahoe. Proceedings of the AWMA International Specialty Conference. Snowbird, Utah, September 26-30, 1994. Aerosols and Atmospheric Optics: Radiative Balance and Visual Air Quality, Volume A, VIP-41. Pp. 835-846.

National Acid Precipitation Assessment Program (NAPAP). 1991. Acidic Deposition: State of Science and Technology, Summary Report, P. Irving, Ed.

Nevada Division of Environmental Protection (NDEP). 1998. 1988-1997 Trend Report, Appendix 3: Ambient Air Quality Data - Gaseous Pollutants, Appendix 4: Ambient Air Quality Data - Particulate Pollutants, Nevada Division of Environmental Protection Bureau of Air Quality.

_____ (Bureau of Air Quality). 1988-1997 Trend Report, Appendix 3: Ambient Air Quality Data - Gaseous Pollutants, and Carb "ADAM" (http://www.arb.ca.gov /adam/welcome.html).

Pedersen, Brian S., and Thomas A. Cahill. 1989. Ozone at a remote, high altitude site in Sequoia National Park, California. Transactions of Effects of Air Pollution on Western Froests, Air, and Waste Management Association. Richard K. Olson and Allen S. Leforn (eds.) Anaheim, California. Vol. 16, pp. 207-220. June 1989.

Phillips, J. 1995. The Crisis in Our Forests, Sunset Magazine, 87-92. July 1995.

Pitchford et al. 1984. Report on the RESOLVE Project in the Mohave Desert. US EPA.

Radke, L. F., et al. 1990. Airborne monitoring and smoke characterization of prescribed fires on forest lands in Western Washington and Oregon: final report. Gen. Tech. Rep. PNW-GTR-251. Portland, Oregon: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Rice, C. L. 1990. Fire history of state parks of the Sierra District of the California Department of Parks and Recreation. Unpublished report. Walnut Creek, California: Wildland Resources Management.

_____. 1988. Fire history of Emerald Bay State Park, California Department of Parks and Recreation. Unpublished report. Walnut Creek, California: Wildland Resources Management.

Scott. E. B. 1957. The Saga of Lake Tahoe. Sierra Tahoe Publishing, Crystal Bay, Nevada.

Sehmel, G. A. 1980. Particle and gas dry deposition. Atmospheric Environment 14:983-1011.

Tahoe Regional Planning Agency. 1991. 1991 evaluation: environmental threshold carrying capacities and the regional plan

package. Zephyr Cove, Nevada: Tahoe Regional Planning Agency.

Turn, S. Q., B. M. Jenkins, J. C. Chow, L. C. Pritchett, D. Campbell, T. Cahill, and S. A. Whalen. 1997. Elemental characterization of particulate matter emitted from biomass burning: wind tunnel derived source profiles for herbaceous and wood fuels. Journal of Geophysical Research, 102, 3683-3699.

Twain, Mark. 1996. Roughing It, Oxford University Press, Chapter 22-23.

USEPA. 1998. National Air Quality and Emissions Trends Report, 1997, Chapter 4. Criteria Pollutants- Nonattainment Areas. US Environmental Protection Agency Document Number 454/R-98-016, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina 27711. December 1998.

_____. 1999. Final Regional Haze Regulation for Protection of Visibility in National Parks and Wilderness Areas, Amendments to 40 CFR Part 51 Subpart P, Code of Federal Regulations. Office of Air Quality Planning and Standards. April 22, 1999.

Van Curen, T. 1996. A Simple Spatially and Temporally Complete Method for Regional Air Pollution Transport Analysis, Report to the GCVTC Technical Committee, Western Governors Assn., Denver, Colorado.

WESTAR Council. 1995. Wildfire/Prescribed Fire Workshop, San Francisco, California. Preliminary notes, G. W. Gause, Editor. November 1995.