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

Atmospheric Modeling of the Lake Tahoe Basin

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

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

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

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

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

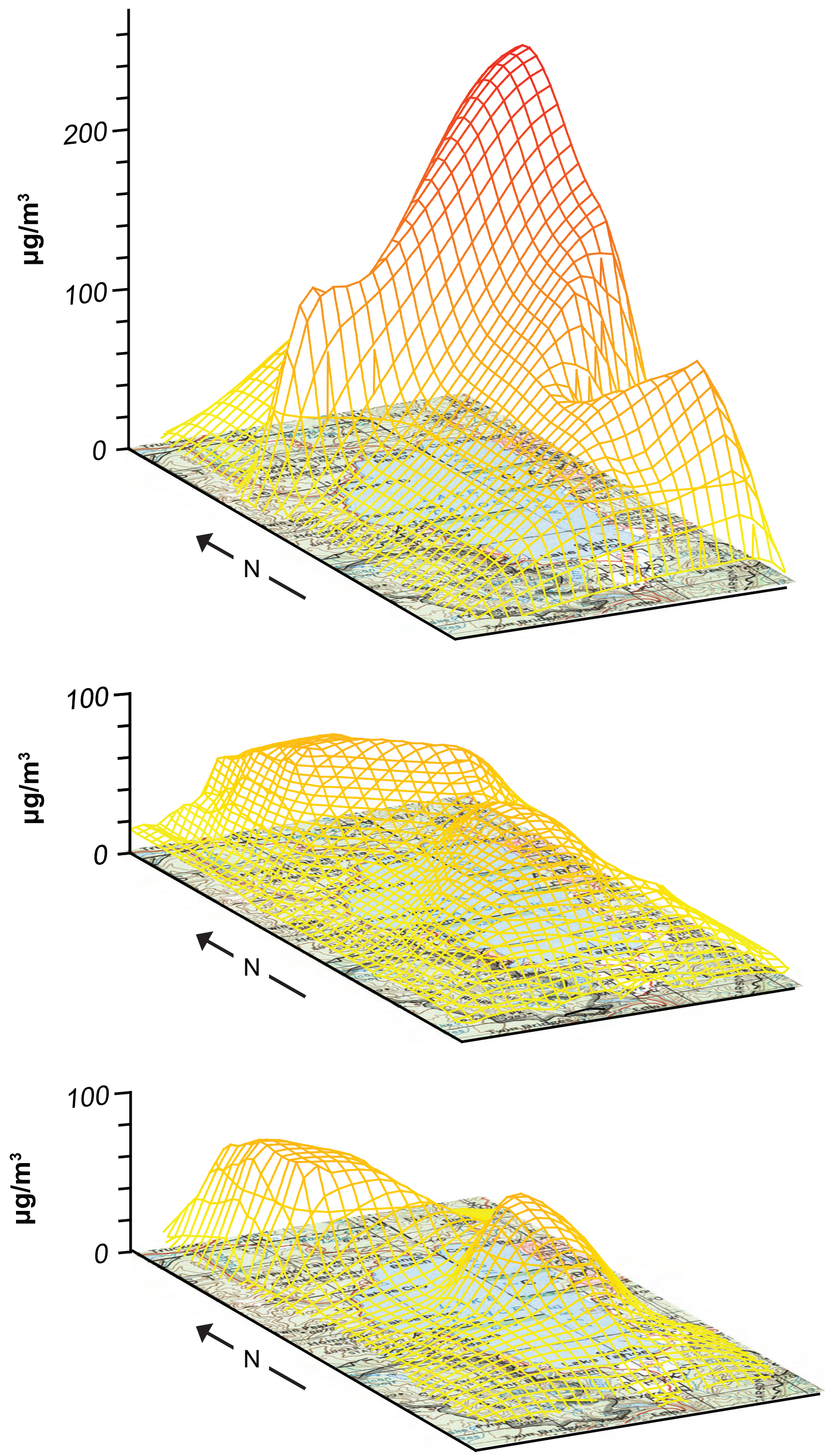

Figure 3.6—Example of Lake Tahoe Atmospheric Model prediction of the evolution of $PM_{2.5}$ from forest fire smoke for 3 days during the Ward Creek prescribed burn. The z-axis represents $PM_{2.5}$ concentrations in $\mu g/m^3$. The bottom graph is day 1 and the top graph is day 3.

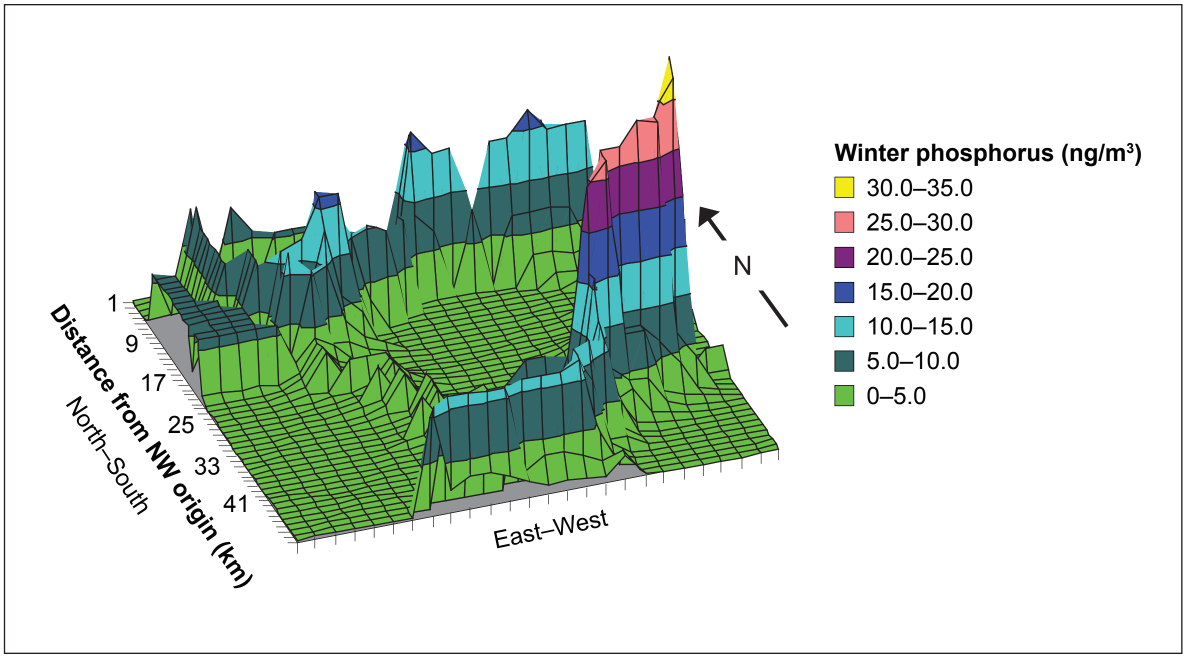

Figure 3.7—Lake Tahoe Atmospheric Model extended to include phosphorus concentrations (ng/m^3) around and over Lake Tahoe. Courtesy of UC Davis Delta Group.

Knowledge Gaps

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

Research Needs

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

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

Impact of Fire on Air Quality

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

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

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

Courtesy of University of Nevada Cooperative Extension

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

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

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

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

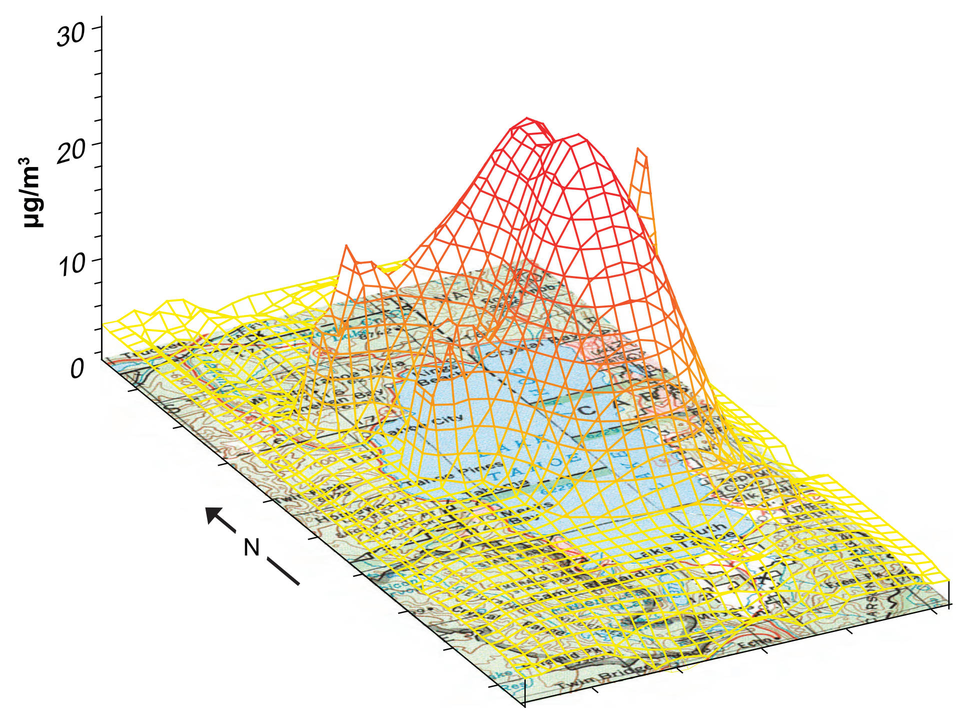

Figure 3.8—Lake Tahoe Atmospheric Model output for $PM_{2.5}$ concentration distribution ($\mu g/m^3$) in the Lake Tahoe basin (underlying map) from historical fire situation based on a 24-hour average.

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

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

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

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

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

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

Scott Hinton

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

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

Knowledge Gaps

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

Research Needs

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