

8. Findings, Insights, and Recommendations

LTADS stakeholders asked ARB staff to develop atmospheric deposition estimates for nitrogen (N), phosphorus (P), and particulate matter (PM). Stakeholders and the TMDL regulatory program needed an improved understanding of the atmospheric sources of N, P, and PM. Finally, stakeholders also desired to know the contribution of air pollution transport, from the Sacramento Valley and the San Francisco Bay Area air basins, to the pollutant burden in Lake Tahoe Air Basin. In response, ARB staff conducted a year-long field study and analyzed the resultant LTADS database. PM was monitored in three aerodynamic size ranges, <2.5 μm diameter (PM_{2.5}), <10 μm diameter (PM₁₀), and total suspended particulate matter (TSP). Concentrations were defined and deposition estimates were prepared for PM_{2.5}, PM_{coarse} (2.5 – 10 μm diameter), and PM_{large} (>10 μm) because the types of sources, chemical composition, solubility, and optical properties may differ markedly with size. Findings and insights gained are summarized by pollutant in this chapter. The potential value of additional research may be considered in the context of the information needs for regulatory decision-making and can be weighed against the resources required and any limitations in feasibility of current or foreseeable methods.

8.1 Deposition Estimates

The LTADS approach for estimating dry atmospheric deposition to Lake Tahoe is based on seasonal-average N, P, and PM mass concentrations being apportioned to seasonal hourly concentrations, based on continuous PM, NO_x, and NO_y measurements. These seasonally-averaged hourly concentrations were then merged with the hour by hour deposition velocities calculated from meteorological variables for each hour of every day to provide hourly dry deposition estimates, which were summed into seasonal estimates. In a less rigorous manner, the wet deposition estimates are based on seasonal air quality concentrations and precipitation frequency but also include an analysis involving basic physical principles and various assumptions regarding mixing heights, washout efficiency, etc.

The estimates from LTADS of the annual atmospheric deposition (dry and wet) of N, P, and PM to Lake Tahoe are presented, with upper and lower bounds, in **Tables 8-1 and 8-2**. CARB staff prepared these final estimates of direct atmospheric deposition to Lake Tahoe based on comments from peer reviewers and additional analyses. The updated analyses include improved formulation of the deposition velocity equations, improved characterization of seasonal ambient concentrations in the four quadrants of the Lake, etc. The seasonal deposition estimates (summarized in **Figure 8-1**) and the characterization of the emission sources and atmospheric processes at work in the Tahoe Basin will be used to guide the development of potential control measures to halt the declining clarity of Lake Tahoe and to restore the water clarity for which the Lake is famous. Background information, approaches, assumptions, and analyses leading to these atmospheric deposition estimates are presented in Chapters 4 and 5 of this report.

The LTADS annual atmospheric deposition estimate for nitrogen is dominated by gaseous N, primarily NH_3 and secondarily HNO_3 , and is consistent with previous deposition estimates based on surrogate surface deposition samplers operated by TRG. However, previous TRG estimates of annual phosphorus deposition to the Lake are almost twice the central estimate for total annual phosphorus deposition from LTADS. Due to difficulties associated with the measurement of phosphorus in particulate matter, the CARB phosphorus deposition estimates use an assumed phosphorus concentration based on the range of P concentrations measured during LTADS and the operational limit of detection for phosphorus in ambient particulate matter samples. It should be noted that the Upper Estimate of P dry deposition to Lake Tahoe assumes the same P concentrations but assumes the maximum, or near maximum, particle size possible for the distribution of P within the particle size categories used for calculation of deposition velocities (i.e., the assumed particle sizes in the deposition velocity calculations were $2.5 \mu\text{m}$, $10 \mu\text{m}$, and $25 \mu\text{m}$ for PM_fine, PM-coarse, and PM_large). Thus, the Upper Estimate essentially maximizes the calculated deposition rate and dry deposition of P. Even the combined Upper Estimates of dry and wet deposition of P are less than half of the historical estimate of P from the TRG surrogate surface samplers. A potential cause of difference between the CARB and TRG P deposition estimates could be a difference in the size of particles collected. CARB's air quality measurements do not include very large particles, such as those associated with plant detritus and pollen, which the TRG surrogate surface deposition samplers, particularly at the tree-impacted site at Ward Lake Level, would include. Because these large particles would not transport long distances, deposition measurements on the shoreline and near trees would not be representative of deposition rates over the whole lake. The P results from the TRG's dry bucket sampler for periods when field notes indicate pollen was present in the sample suggest that natural sources could be a significant source of P input to the Lake.

Table 8-1. LTADS Estimates of Annual Dry Atmospheric Deposition to Lake Tahoe
(metric tons/year)

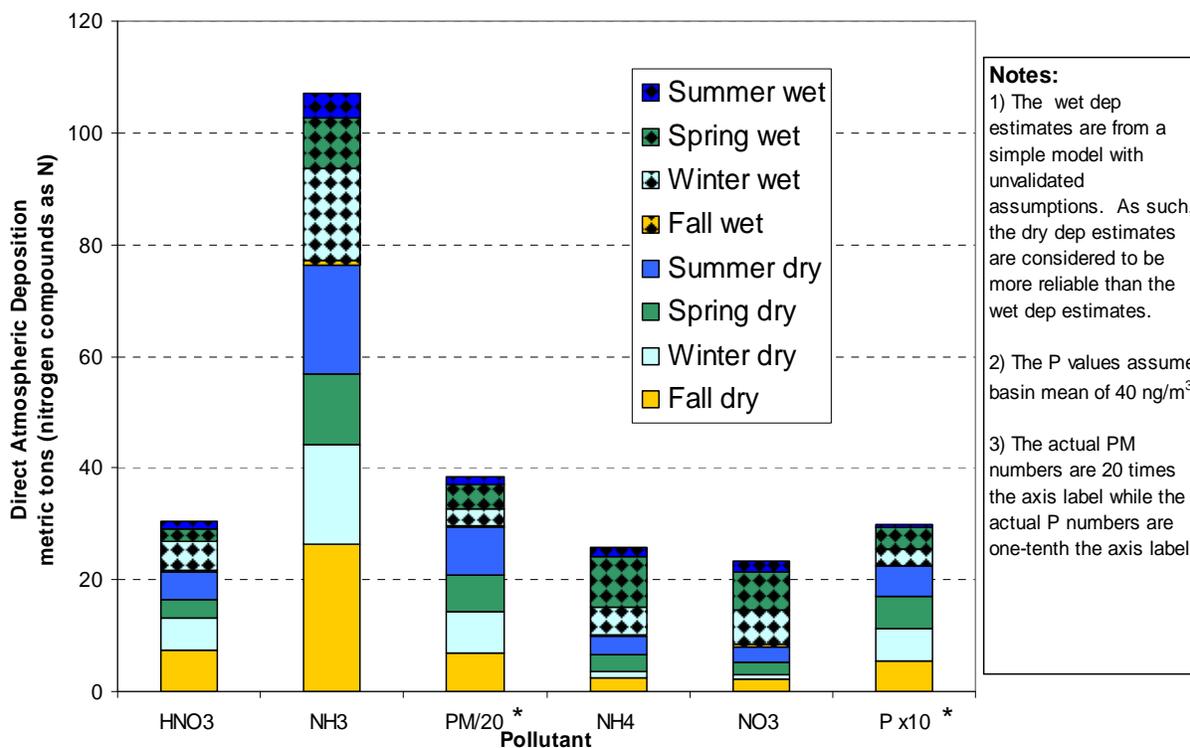
Pollutant	Lower Estimate	Central Estimate	Upper Estimate
N (NH ₃ , NH ₄ ⁺ , HNO ₃ , NO ₃ ⁻)	70	120	170
P (P, PO ₄ ⁻³)	1	2	3
PM_fine (<2.5 μ)	50	60	62
PM_coarse (>2.5μ and <10μ)	100	170	240
PM_large (>10 μ)	210	360	560
PM	360	590	860

Table 8-2. LTADS Estimates of Annual Wet Atmospheric Deposition to Lake Tahoe*
(metric tons/year)

Pollutant	Lower Estimate	Central Estimate	Upper Estimate
N (NH ₃ , NH ₄ ⁺ , HNO ₃ , NO ₃ ⁻)	30	70	150
P (P, PO ₄ ⁻³)	0	1	2
PM_fine (<2.5 μ)	30	75	145
PM_coarse (>2.5μ and <10μ)	30	70	130
PM_large (>10 μ)	10	20	40
PM	70	165	315

* The wet deposition estimates are based on a basic principles analysis with un-validated assumptions.

Figure 8-1. LTADS Central Estimate of Seasonal Total Atmospheric Deposition to Lake Tahoe.
(metric tons/year)*



* Note adjustment to PM and P values. Actual PM dep is 20 times greater and actual P dep is 10 times less than indicated on Y-axis.

8.2 Particulate Matter

8.2.1 Findings

Measurements of particulate matter (PM) were made in three sizes (TSP, PM10, and PM2.5) with the Two-Week Sampler from late 2002 through 2003 at four locations in the Tahoe Basin. These data from the TWS network provide spatial, temporal, physical, and chemical insights into the nature of PM in the Tahoe Basin. Conclusions about the mass and speciation of TSP and PM10 are similar because coarse and large particles are generally emitted by the same sources and only a small portion of the TSP was present in sizes greater than 10 microns. The highest concentrations of atmospheric PM were found in places with the largest population and greatest vehicular traffic. Geographically, the highest levels of PM were observed during LTADS, in order of magnitude, at South Lake Tahoe (SOLA & Sandy Way sites), Tahoe City (Lake Forest), and Thunderbird Lodge. At the high PM locations, seasonal concentrations, in decreasing order, tended to be highest during winter, lower during summer and fall, and lowest during spring. At the low PM sites, concentrations, in decreasing order, tended to be highest during summer, lower in fall and spring, and lowest in winter. Thus, the high PM concentrations were coincident with proximity to vehicular traffic and with high

traffic seasons. These observations support the hypothesis that roadways and vehicular traffic are a major source of the atmospheric TSP in the Tahoe Basin.

For the locations with higher PM concentrations (Lake Forest, Sandy Way, & SOLA), the PM10 mass comprises between 75% and 85% of the TSP mass. At the location with the lowest PM concentrations (Thunderbird), PM10 and TSP concentrations were roughly equal and thus indicating that particles larger than 10 μm were generally not significant contributors to the TSP concentrations at locations isolated from local influences. This pattern is consistent with expectations that the relative concentrations of TSP, PM10, and PM2.5 mainly reflect their relative emission fraction close to a PM source and that the relative contribution of the larger, heavier particles would decline significantly with distance from a source.

Due to deposition and dispersion, atmospheric TSP concentrations decline substantially from the populated areas and roadways (Lake Forest – north, SOLA – south) to piers (Coast Guard pier – north, Timber Cove pier – south). Low population and low vehicular traffic areas (Bliss – west shore & Thunderbird – east shore) have dramatically lower TSP concentrations (1/5 of the high population, high vehicular traffic locales). Mid-lake TSP concentrations (buoys west & east) were similar to areas with minimal local emissions. Depending on wind direction, the closer a sampler was to vehicular traffic, the higher the TSP concentrations tended to be. Furthermore, the use of continuous monitors (BAM) rather than filter samples, frequently documented large temporal changes in PM concentrations when wind directions changed as well as documenting that the highest TSP and PM10 concentrations occur during the morning and evening commute periods, especially when winds were light and temperature inversions were present near ground level. These observations strongly support the hypothesis that roadways and vehicular traffic are a major source of atmospheric TSP and PM10 in the Tahoe Basin.

The majority of the PM mass is composed of (in order of total mass) soils, organic materials, particulate nitrogen, and elemental carbon. The composition of the PM also supports the hypothesis that roadway traffic is a major source of TSP emissions in the Tahoe Basin.

The observations and conclusions for PM_{fine} (i.e., PM2.5) have some similarities with and differences from those of the larger particles. First, the highest concentrations of atmospheric PM2.5 were also observed in places with the highest population and greatest vehicular traffic while the lowest PM2.5 concentrations were observed at the more remote Thunderbird site. At the locations with high PM concentrations (i.e., Lake Forest, Sandy Way, & SOLA), the PM2.5 mass was 30% to 40% of the TSP mass. At the location with low PM concentrations (Thunderbird), PM2.5 comprised 60% of the TSP mass. Seasonal PM2.5 at high concentration locations was much more variable than observed for the larger PM particles, with the only common feature being that the lowest PM2.5 concentrations occurred during spring. PM2.5 concentrations at the low concentration location (Thunderbird) varied seasonally, being highest during summer, lower in fall, lower still in spring, and lowest during winter.

Likewise, particles collected close to a source of gaseous or fine particle emissions are expected to contain more of the volatile chemical species such as nitrates and ammonium ion in the fine fraction. Far from a source, atmospheric processes are likely to allow accumulation of some of these volatile species onto larger particles. At locations with high PM_{2.5} concentrations (Lake Forest, Sandy Way, & SOLA), nearly all ammonium ions and 70% to 85% of the nitrate ions were in the PM_{2.5} fraction. At the location with lowest PM concentrations (Thunderbird), more than 35% of the ammonium ion and 55% of nitrate ions are in the PM_{fine} size fraction. The nighttime increase in PM_{2.5} observed at SLT-Sandy Way during the winter indicates that wood smoke is a contributor to PM_{2.5} concentrations.

8.2.2 Insights

The historical dry deposition measurements by the TRG rely on surrogate surface samplers, which can potentially capture any size of particle, including very large particles (e.g., insects, plant detritus, and pollen). These large particles, which can be seen in the air near sources, have relatively short atmospheric lifetimes and typically do not transport more than a few tens or hundreds of meters. In contrast, these large particles are not measured by typical air quality sampling instruments. Thus, the type of sampling equipment and the proximity to local PM sources can drastically affect measurements and interpretations of the data.

A series of dust experiments that were conducted between the shoreline and a road demonstrated that particle number concentrations, especially for larger particles, decline significantly from the roadway to the shore. Although deposition and dispersion from roadways to the shoreline and potentially to mid-lake are not completely characterized by these spatially and temporally limited measurements, it is clear that local emission sources and their proximity to the lake are important. Additional characterization of spatial variations in particle number and concentration and the resulting refinement of annual deposition estimates would require additional measurements.

8.3 Nitrogen

8.3.1 Findings

Total nitrogen concentrations (both gaseous and particulate) were observed at the four in-basin TWS sites. At all these sites, particulate N amounted to no more than 5% to 10% of the TSP mass. However, the particulate N accounted for roughly 30% of the total N observed in high-traffic, populated areas but an even greater 60% of the total N observed in the less populated receptor areas. Inversely stated, gaseous N (i.e., ammonia and nitric acid) comprised 60% to 80% of the total N at the high N sites while only 40% of total N was gaseous N at the low N site.

Ammonia concentrations were highest at SOLA, followed by Sandy Way, Lake Forest, and lowest at Thunderbird Lodge. Nitric acid concentrations followed a similar pattern. At the locations with the highest concentrations (SOLA, Sandy Way, and Lake Forest),

ammonia concentrations peaked during winter and fall, were lower during summer, and lowest during spring. At the site with low ammonia concentrations (Thunderbird), ammonia concentrations peaked during summer-fall and were lowest during spring-winter. Much higher ammonia concentrations were measured in South Lake Tahoe. Nitric acid concentrations in the southern Tahoe Basin were highest in winter, lower in fall, lower still in summer, and least in spring. Nitric acid concentrations in the northern Tahoe Basin were highest in summer-fall and lowest in spring-winter. Thus, substantial seasonal differences were seen between nitric acid concentrations at Lake Forest and South Lake Tahoe.

Particulate nitrogen (ammonium and nitrate ions) concentrations from the TWS and MVS networks were difficult to compare because TWS was equipped with back-up filters for catching nitric acid (but not ammonium ion) and MVS was not. Nevertheless, observed particulate nitrogen concentrations differed between the southern, northern, and remote locations. The particulate N concentrations were 25% higher at South Lake Tahoe (SOLA & Sandy Way) than at Lake Forest and Thunderbird, where the study-average concentrations were roughly the same. West shore (Wallis Residence & Coast Guard) and east shore sites (Zephyr Cove) had generally lower particulate nitrogen concentrations than mid-lake buoys. Mid-lake particulate nitrogen concentrations most resembled concentrations at the south shore (Timber Cove).

8.3.2 Insights

Ammonia and nitric acid measurements are technically difficult and the denuder method provides no exception to these difficulties. Separate measurements were not made for nitrous acid, but nitrous acid concentrations are a positive artifact in the HNO_3 measurements. Thus, nitrous acid was represented in the HNO_3 measurements and the subsequent estimates of nitrogen deposition. The stability of ammonia measurements over the two-week sampling period was a significant unanswered issue. No mid-lake gaseous nitrogen data were collected.

Particulate nitrogen observations were limited by lack of a back-up filter for ammonium ion and no back-up filters for other volatile species. For samples collected with the MVS, almost half of the ammonium ions and likely a molar equivalent amount of the nitrate ions may have been lost because back-up filters are not feasible with this instrument.

8.4 Phosphorus

8.4.1 Findings

From over six hundred possible (TWS & MVS) ambient samples, zero samples were observed with concentrations above the measurement uncertainty limits. Interestingly, the four highest concentrations greater than 15 ng/m^3 (minimum detection level) were recorded for Thunderbird Lodge (27.3 ng/m^3 ; invalid due to low air flow), the Coast Guard pier (21.0 ng/m^3), Lake Forest (16.4 ng/m^3), and SOLA (15.1 ng/m^3).

Based on reanalysis of the filters by UC Davis using a different X-Ray Fluorescence (XRF) method with better limits of detection, it appears that the originally quoted limits of P detection (based on a pure sample) were two or more times lower than under real-world conditions where silicon (Si) and sulfur (S), which have XRF signals that overlap with that of P, are common elements in the PM sample. Often when the original data indicated high concentrations, the reanalysis indicated low concentrations and vice versa. Thus, there was difficulty in detecting P, not only for ambient samples but also for source samples.

Although staff attempted a number of different methods, it is apparent that atmospheric phosphorus is very difficult to measure. With XRF, the primary method used in LTADS, the P measurement is subject to interference from overlapping signals of other, much more abundant elements in ambient PM samples, which have a large soil component. Furthermore, the x-ray emissions can be self absorbed by other P atoms in the particle. The magnitude of the correction for this self absorption depends strongly on the size and composition of PM greater than 2.5 μm . Based on analyses of measurement uncertainties, source profiles, P concentrations reported for other non-urban areas of the State, and so forth, staff concluded that the average P concentration in the Tahoe Basin is between 20 and 40 ng/m^3 , with the upper limit very unlikely to be exceeded as an annual average for the Basin.

8.4.2 Insights

Using standard methods, P measurements are difficult in ambient PM due to interferences from S and Si. LTADS attempted alternative methods to measure P such as the Inductively Coupled Plasma Mass Spectrometry (ICPMS); however, this alternative method was not helpful. The synchrotron XRF method used by UCD showed improved measurement sensitivity but did not detect a higher maximum P concentration than reported by standard XRF. Additional review indicated that the current analytical quantification techniques, which are reasonable for small particles (PM_{2.5}), are likely not appropriate for large particles due to greater self absorption of the x-rays. The self absorption corrections depend strongly on the size, composition, and distribution of P (also Si and S) within the particle, information not generally available.

8.5 Air Pollution Transport

8.5.1 Findings

The transport of pollutants in any significant measure from the San Francisco Bay Area and Sacramento Valley air basins to the Tahoe Basin is counter-indicated by meteorological processes. Upslope surface winds are typically too slow to transport significantly high concentrations of pollutants the full distance to the Tahoe Basin before surface winds reverse in the evening (due to density-driven drainage flow as the mountain slopes cool). Big Hill was established as a comprehensive monitoring site upwind of the Tahoe Basin during LTADS. This site was also located well away from local influences and well situated to provide a good indication of any potential for

regional and global transport impacts. However, because Big Hill is below and west of the crest of the Sierra Nevada, it is possible for pollutants to reach Big Hill but still not reach the Tahoe Basin. Furthermore, any air flow over the Sierra crest, whether at the surface or aloft, would also need to be mixed vertically down to the lake surface; this mixing with typically cleaner air would dilute pollutant concentrations before reaching the Lake.

In addition to the physical (geographical and meteorological) constraints, deposition and chemical reactions also act to reduce the impact of pollutant transport. Although the mountain counties receive some air parcel transport from Sacramento, Bay Area, and San Joaquin Valley air basins, reactive nitrogen species, such as nitric acid, nitrates, and total reactive nitrogen (NO_y) probably do not survive sufficient time to be transported in significant measure from the San Francisco Bay Area, San Joaquin, and Sacramento air basins to the Tahoe Basin. Organic nitrates tend to have longer lifetimes in the atmosphere than other nitrogen species but they also have low deposition velocities. In general, when local pollutant sources are present, they will exert more influence on ambient concentrations than do upwind NO_y sources.

Measurements during UCD aircraft flights over the lake in late summer and fall of 2002 indicate the possibility of ammonia transport. During a boat sampling transect along the western shore of the Lake late one afternoon, a spike observed in ozone and PM_{fine} concentrations indicated the possibility that an aged, polluted air mass was transported through a col in the Sierra Nevada crest.

The peak TSP concentrations at Big Hill occurred during summer and fall (50% higher than the rest of the year). During summer and fall, the southern and northern regions of Tahoe had 25% more TSP than Big Hill. These seasons have potential for both transport (due to longer days and solar induced upslope air flows) and local dust emissions (due to increases in traffic with dry conditions).

8.5.2 Insights

Local emissions account for most of the observed concentrations of air pollutants that are higher than typical regional and global background levels in the Tahoe Basin. However, some primary pollutants (such as ammonia) that have abundant and ubiquitous upwind anthropogenic and natural sources and secondary pollutants, such as ozone, may survive the transport processes (e.g., mixing, dilution, deposition). Transport may contribute to increased background concentrations of ammonia and ozone in the Tahoe Basin. Meteorological process and ambient air quality data do not support the concept of 1-day transport to the Tahoe Basin of highly polluted air masses.

No significant wildfires occurred during LTADS and so staff collected no ambient data to address the magnitude of the impact of smoke from wildfires on N, P, and PM deposition to the Lake. Wildfires undoubtedly input a large amount of these pollutants into the atmosphere as has been confirmed by specie profiles of source samples as well as limited ambient measurements in smoke plumes. However, the magnitude of the actual impact depends on the size, location, and duration of the fires as well as the

associated meteorology (elevated plumes, inversion layers, wind direction). The actual deposition to the lake of these emissions, which are limited in time and space relative to year-round processes, is not easily known. It is not obvious to staff that smoke plumes from episodic large-scale fires outside the basin, although impressive in their immediate impact, are likely to contribute much to the annual loading of PM, P, or N to the lake itself.

8.6 Source Characterization

LTADS source characterization efforts were intended to improve understanding of a few selected sources with potentially significant contributions to atmospheric deposition. The LTADS efforts related to the Tahoe emission inventory in no way represent a comprehensive assessment or characterization for emissions within the Tahoe Basin. With this in mind, staff cautiously offers the following summary.

8.6.1 Findings

LTADS provided detailed (though by no means definitive) characterization of particles associated with road dust and wood smoke from prescribed fires and wood stoves. On average for wood smoke (PM₁₀ & PM_{2.5} filter) samples, nitrate concentrations were 0.15%, ammonium ion was 2.55%, and P was below 0.01%, while organic carbon comprised 49% and elemental carbon nearly 9% of the mass. The source specific wood smoke results are very similar to the neighborhood wood smoke results.

On average for roadside dust samples, PM nitrate concentrations were 0.25%, ammonium ion was 0.46%, and P was not detected, while organic carbon was 34%, elemental carbon was 8%, aluminum was 3%, and silicon was 12% of the mass on the filters (PM₁₀ & PM_{2.5}).

Multiple experiments and data analyses indicated that motor vehicles and population centers exerted a strong influence on PM, ammonia, and NO_y concentrations. The BAM PM_{2.5} measurements on the rooftop at Sandy Way exhibited a clear impact of wood smoke during winter evenings.

8.6.2 Insights

Very low concentrations of P and particulate nitrate in the wood smoke samples support the hypothesis that wood smoke is not likely a significant source of P and particulate nitrate. Ammonia might be emitted in significant quantities in wood smoke but these measurements did not include gaseous data collection. LTADS source characterization efforts had insufficient resources to properly compare particulate nitrate and ammonia emissions from these natural combustion sources versus motor vehicles.

The December 14, 2005 LTADS workshop at Tahoe concluded that gathering basic information in both California and Nevada (e.g., population, land use, prescribed burning, wildfire, visitor information, and hotel/motel occupancy data) was still an unmet need for developing proper emission inventories for the Tahoe Basin.

8.7 Meteorology

LTADS meteorological instrumentation included remote sensing equipment to characterize the upper air, including mini-sodars (measuring horizontal winds within 100 meters of the ground level), radar wind profilers (vertical and horizontal winds from 100 meters up to several kilometers above ground level), and radio acoustic sounding systems (temperatures from 100 meters to nearly one kilometer above ground level). In work not sponsored by LTADS but applicable to addressing LTADS issues, the Desert Research Institute (Professor Gayle L. Dana) conducted micrometeorological measurements (vertical flux of heat, water vapor, and momentum) within a few meters of the Lake surface. All of these data are in the early stages of analysis.

8.7.1 Findings

Winds observed at surface sites in the Tahoe Basin display temporal regularity with daily oscillation between onshore and offshore flow due to the mesoscale influences. However, spatial variations are important as well. In particular, the on-shore and off-shore flows have complexities in terms of their horizontal extent and their depth which are not defined by point observations. In some areas of the Lake (e.g., east and northwest), the interaction of meso- and synoptic scale influences can regularly result in flows parallel to the shore with little transport of air pollutants from the shoreline onto the Lake.

8.7.2 Insights

Characterizing the spatial variability of the winds at Tahoe is a challenge due to the forested nature of the Basin and the small scale terrain influences that limit the spatial representativeness of any near ground measurements. Because the mini-sodars are much quieter and require less space and power, they are easier to site than radar wind profilers with RASS, but they do not serve the same purposes. The vertical range of mini-sodars is much less and depends in part on the specific humidity, which is limited by the cooler temperatures at Tahoe compared to lower elevations. The vertical range of the mini-sodar is also limited by ambient noise. Flows below a few tens of meters, which are critical for estimating atmospheric deposition to the Lake, are strongly influenced by the most local terrain features, especially during drainage flows. Flows to a few hundred meters or more above ground level can be strongly influenced by the thermal differences between land and lake surfaces and by the larger scale terrain features.

8.8 Surrogate Surface Deposition Methods

LTADS included a special study to compare surrogate surface methods of measuring dry deposition. It was hoped that the analysis would provide consistent relationships that would permit deposition measurements among surrogate surface samplers to be reconciled. However, the limited and variable results in the surrogate surface methods comparison precluded definitive relationships and adjustment of historical data to better characterize the actual deposition associated with the most representative method. Wet

and dry deposition assessments based on ambient air quality data and meteorological conditions provided in this report were in crude agreement with measurements during 2003 by the TRG bucket method.

8.8.1 Findings

The continuous water surrogate surface deposition sampler (WSS), which conceptually would provide the most representative measurement of dry deposition to a water surface, will require upgrades to increase its robustness for field comparisons with the “buckets.” Wind action, deposits of plant and insect materials, and desiccation all create difficulties in interpreting surrogate surface deposition data or making comparisons with deposition estimates calculated from meteorological and air quality data.

8.8.2 Insights

Improved siting of the “bucket” samplers would improve comparability with air quality measurements. An improved operational design for the WSS would include shorter periods for sample collection (e.g., 24-hour) and sample analysis (e.g., weekly).

8.9 Potential for Future Research and Utility of Narrowing Uncertainty in Deposition Estimates

The primary purpose of LTADS was to provide an independent estimate of the direct atmospheric inputs to Lake Tahoe of air pollutants potentially reducing water clarity. These estimates were used in developing a TMDL that incorporates pollutant inputs to the lake from air, streams, land, and underground. The ranges of the lower, central, and upper estimates of atmospheric deposition incorporate both uncertainties in the measurements and scientific judgments of the possible effects of poorly known sources of variation, such as particle size distributions. The range of estimates provided in the main body of the report (Chapters 4, 5, and 8) and in Appendix M also reflect judgments about spatial variability of concentrations and deposition velocities as they may differ from the conditions at the monitoring sites, due to the distribution of sources, drainage winds around the lake, and upper level winds over the lake.

The significance of uncertainties in the deposition estimates is not the numbers themselves but the relative benefit it would make to the TMDL and Tahoe Basin water quality control programs if the ranges for the estimates of deposition were narrowed. More specifically, the range of estimated deposition rates is only an issue for those pollutants for which the TMDL interpretation or list of possible control options is different for the upper and lower estimates. For example, if even the lower estimate for a pollutant's input to the lake is deemed excessive in the TMDL, then narrowing the range would have no regulatory significance. Conversely, if even the upper estimate for a pollutant's input is deemed insignificant in the TMDL, then narrowing the range also would have no regulatory significance. Similarly, if the list of potential emission control strategies for a particular pollutant would not be different at either end of the range, then

narrowing the range of deposition estimates for that pollutant would have no regulatory significance.

If the TMDL review or subsequent development of water quality control strategies determines that strategies should differ substantially if the actual atmospheric deposition rate falls at one end of the range of estimates versus the other, then there is practical reason to attempt to narrow the range of estimates. In this case, the potential for additional research to narrow the range of estimates would presumably be critically considered along with the cost and the probability of successfully delivering more definitive information. The following paragraphs summarize and comment upon potential research approaches, some of which the LTADS investigators believe, based on their experience, would be productive avenues to narrow uncertainties in the atmospheric deposition estimates.

As air quality specialists, the LTADS investigators cannot anticipate how the current estimates will be used in the TMDL process, nor can they anticipate which, if any, of the ranges of estimates will leave uncertainty in the selection and priority of potential strategies for mitigation. Indeed, some of the choices for mitigation strategies may be entirely dependent on best available controls and independent of the current range of deposition estimates.

The following discussions are intended solely as informal guides to help the responsible agencies understand the types of research efforts that the LTADS investigators believe would be more or less productive for narrowing uncertainties *assuming such a narrowing is deemed necessary*.

8.9.1 Potential Approaches for Narrowing Estimates of Nitrogen Deposition

If refinement of nitrogen deposition estimates would lead to changes in mitigation methods, there are several potential approaches that could be considered. Better spatial and temporal resolution of ammonia and nitric acid concentrations through land-based measurements might be less valuable than making on-lake measurements. However, land-based measurements would probably be more feasible and would improve the estimates of deposition and increase understanding of the possible sources. This information could also be important to planning the locations of on-lake measurements, if those are pursued. Some attention to South Lake Tahoe as the location with higher concentrations of gaseous nitrogen concentrations and possible nitric acid measurements at northern Tahoe basin might be warranted. In spite of the logistical difficulties, if nitrogen deposition estimates need to be narrowed, then collection of gaseous nitrogen concentrations over mid-lake areas would be an important additional measurement.

Particulate nitrogen concentrations could also be considered but appear to be much less important to the total nitrogen input. Although particulate nitrogen was not a large contributor to the estimated deposition of total nitrogen, simultaneous observations of gaseous and particle nitrogen would provide a better view of the overall nitrogen

chemistry. Similarly, back-up filters for volatilized ammonium and nitrates would be warranted, if additional particulate nitrogen measurements are needed.

A more difficult and less useful approach to quantifying concentrations over the Lake would be to directly measure the advection of nitrogen species across the shoreline. This would be difficult due to requirements for vertical resolution and also because of the limited temporal resolution of the current measurement methods for ammonia and nitric acid. The following is not necessarily recommended but is included as a cautionary note. If multi-hour sampling times were required to acquire sufficient sample volume or control analytical costs, then longer term sampling, conditioned on wind direction, should be considered. It would be unwise to commit to such a program, however, prior to the demonstration of its feasibility through rigorous pilot projects.

8.9.2 Potential Additional Research on Phosphorus

If a narrowed range of estimates of phosphorus deposition would alter mitigation decisions, then the first need would be for better quantitative measurement of P concentrations in particles and source materials. For improved measurement methods, additional preparatory research would be needed to quantify the self absorption correction factors appropriate for large particles that are typically found in road dust. Pilot studies to ascertain the implications of field and lab blank concentrations on a site-by-site basis would also be required.

Improved characterization of the spatial variations in phosphorus concentrations would also be a key element of refined estimates of deposition. Thus, collection of samples over the Lake would be very important.

More definitive information on the P content of Tahoe-specific soils, pollen, plant detritus, wood smoke, prescribed fires, and motor vehicle emissions are all potential avenues for improvement of P deposition estimates and water quality control decisions.

Improved characterization of the size and sources of particles could potentially supply phosphorus to the Lake would also be a key element in the refinement of deposition estimates. We note that there is a potential mismatch between sampling methods due to differences in collection efficiencies based on particle size. Air quality monitoring is generally not intended to collect the very large particles with relatively high gravitational settling velocities. On the other hand, P deposition estimates with wet/dry bucket surrogate surface sampling, if located near a source of large particles, would likely collect those larger particles (and if very near such a source might over-represent such particles). Larger particles may include natural materials such as plant detritus or pollen.

8.9.3 Potential Additional Research on Wind Fields

Three-dimensional wind fields for the Tahoe Basin could be developed to resolve more of the complexities of transporting particulate matter and nutrients from the shoreline to mid-lake. If wind field development is undertaken with modeling, it should be with the

recognition that the existing upper air measurements, although ambitious and not previously available for Tahoe, are still very limited compared to the spatial complexity they are intended to represent. In particular, within the Basin, only one measurement location (South Lake Tahoe Airport) provides wind or temperature data at heights above the limited vertical range of the three mini-sodars. Thus, extensive evaluation of the performance of meteorological models is probably not possible with the existing data. However, the LTADS RWP/RASS and mini-sodar data are available for comparison with the 2003 wind and temperature fields developed by the MM5 modeling that was conducted to create the historical database of precipitation and freezing levels necessary for the watershed runoff modeling. Such a comparison effort would provide spatial and temporal reference points for characterizing the general performance of the MM5 model used in the precipitation runoff analyses.

The LTADS meteorological data and the previously collected flux data, such as Professor Dana's work, should be fully analyzed and evaluated before additional measurements are considered. Using these data, we recommend a fuller exploration of wind trajectories and the fluxes at the lake surface-air interface.

If future studies attempt the ambitious task of more fully characterizing 3-dimensional meteorological fields, then additional upper air measurements, such as additional radar wind profilers with RASS or episodic deployment of rawinsondes, should be considered to provide more complete spatial coverage for areas around the lake where RWP/RASS cannot not be sited. With additional measurements, there would be the potential for a robust evaluation of the performance of meteorological models; for example, evaluations for simulations overlapping periods with supplemental upper air (e.g., rawinsonde) observations. Such a program might include instrumentation on additional buoys and releasing rawinsondes from multiple piers. If well-designed, there might be a potential for co-funding for such a measurement program from parties with a purely meteorological interest.

8.9.4 Potential Additional Research for Direct Observation of Air-Water Fluxes

Although an ambitious meteorological program may not be justified solely for refinement of deposition estimates, there would be benefit in obtaining simultaneous flux measurements of the exchange of momentum, heat, and water vapor between the atmosphere and the lake. Consideration of a more complete suite of measurements could potentially attract expertise and funding from the boundary layer meteorology community.

A very useful observation would be direct measurements to characterize vertical fluxes over the lake (i.e., the exchange of some trace gases or particles between the atmosphere and the water surface). Such measurements, possibly by eddy covariance method, would require great care for site selection and evaluation of spatial representativeness. If eddy covariance observations of trace gas or particle fluxes are not logistically or financially feasible, eddy covariance measurements of meteorological (momentum, water vapor, and heat) fluxes, could still be possible. They would be useful for comparison with those values inferred in the course of estimating deposition

velocities. The realities of constraints on access to potential sites and limitations of those sites with respect to representative results should be considered along with their implications for the usefulness of the resulting measurements. Only with such a view could the potential value of flux measurements be realistically weighed against the direct costs and opportunity costs.

8.9.5 *Potential Additional Research of Surrogate Surface (Bucket) Samplers*

The relative loading of surrogate surface samplers, compared with the rate of dry deposition to water, may differ with environmental conditions such as wind speed and with particle size or chemical characteristics of gases. The dependencies and variability are complex and have not been quantified. Thus, interpretation of results is problematic. These issues are universal to many studies beyond Tahoe and have not been resolved. An additional controlled experiment with a water surface sampler, the “buckets,” and air quality measurements could be considered to provide a rough guide for comparisons. However, because multiple variables are likely important, such a comparison should not be expected to provide a formula for translating results between methods. Equally, or perhaps more significant, for any deposition sampling with surrogate surface samplers in the Lake Tahoe Basin are the practical issues of siting the samplers to ensure better spatial representativeness of the measurements.

8.9.6 *Potential Additional Research of Atmospheric Budgets by Direct Observations*

In theory, atmospheric budgets based on measurements could be helpful to constrain the estimates of deposition to the lake. Some have suggested observation-based budgets to characterize the advection of pollutants into and out of the Tahoe Basin. However, the spatial complexity of the Basin boundaries and logistical constraints (e.g., lack of potential sites with electrical power), and potential differences in concentration in and above the forest canopy make such an endeavor logistically infeasible. The spatial and temporal complexity of winds, vertical mixing, and concentrations would also make it very difficult to construct an observationally based pollutant budget for a mass balance of advection and deposition over the lake. Although a pollutant budget for the atmosphere over the Lake might be possible, significant uncertainties (e.g., due to undefined variation in vertical mixing with distance downwind from the shoreline) would remain despite large expenditures for a reasonable density of observations. Such an atmospheric budget would require a vast increase in monitoring resources compared to those utilized in LTADS.

To illustrate the complexity and resources required, note that vertical profiles of pollutant concentrations and winds would be needed to characterize advection (horizontal flux across a vertical plane near the shoreline) as one element of such a program. A high density of measurements would be required due to the spatial complexity of the terrain, meteorological fields, and concentrations. Vertical profiles are difficult and expensive to determine and ideal measurement heights to characterize profiles of concentration could be expected to differ between pollutants. Temporal differences associated with wind shifts are also a concern. Some species are currently only measured with filters or

denuders that require relatively long sample times for sufficient sample volume. Thus, for some chemical species, it might only be feasible to sample conditionally, based on wind direction, to provide some inference of temporal variations necessary to characterize horizontal fluxes. The possible benefits of such measurements should only be considered in the context of the resources required and realistic acknowledgement of the uncertainties that would likely remain. They should not be undertaken without successful demonstration of methods via smaller pilot studies.

8.9.7 Potential Additional Research of Transport

Although literature reviews and additional analysis of the historical and LTADS data could provide more insights on the relative importance of local and transported emissions, the results are unlikely to be as quantitative as desired due to the limited number of monitoring sites and the complex topography and meteorology.

Definitive direct monitoring of transport above the surface layer is difficult and expensive in any setting. Further, for the Tahoe Basin, the complex meteorological setting and the relatively clean air near and within the Basin makes it difficult to differentiate a transport component from the natural and local components. Observational studies with sufficient horizontal and vertical resolution to more accurately quantify transport would be very expensive, if feasible at all. The cost seems far out of proportion to any benefit of small improvements in quantification. For these reasons, staff has not recommended additional air pollution measurements to assess transport.

8.9.8 Potential Additional Research of Emission Sources

Atmospheric phosphorus that could participate in deposition appears to be primarily of geological origin. However, natural input of phosphorus from plant detritus may also be important. Possible contributions of phosphorus by smoke from residential wood combustion, planned fires, and wildfires are likely minor compared to geological sources. However, despite this basic understanding of likely phosphorus sources, collection of more source profiles for refining pollutant emission factors may be useful to add certainty and guide control strategies. Additional enhancement of the fire database for the Tahoe Basin, including statistics such as acres burned (prescribed and wild fire), fuel condition, etc., could support more comprehensive analyses. Literature reviews and analyses of global air pollution transport may be of scientific interest and provide information on the possibility of P transport (e.g., in Asian dust) but is unlikely to be relevant to the selection of control strategies for phosphorus in the TMDL.

Compared to particulate nitrogen, gaseous ammonia and nitric acid appear to be far more important contributors to the total direct atmospheric deposition of nitrogen to the Lake. The emission sources for these compounds or their precursors have not been fully characterized and future investigations should also consider measurement difficulties.

8.9.9 Potential Additional Research to Improve Measurement Methods

Because ambient concentrations are low in the Tahoe Basin, many of the measurements were at, or below, the sensitivity of the measurement methods. Improved measurements of phosphorus, ammonia, nitric acid, and speciation of particulate matter would be helpful to the Lake Tahoe efforts. Improvement of measurement methods is a more general scientific need which, if addressed by the larger scientific community, could provide opportunity for further investigations in the Tahoe Basin. With improved sensitivities, better characterization of ambient concentrations and emission rates would be possible, especially for phosphorus, ammonia, and nitric acid.

8.10 Summary

LTADS was a multi-million dollar effort with contributions of funds and efforts by many agencies and groups. LTADS addressed issues of relevance to the TMDL stakeholders, providing refined atmospheric deposition estimates and improved understanding of emission sources and atmospheric processes. LTADS was the first atmospheric study to collect detailed ambient air quality samples continuously throughout a year. LTADS also featured continuous meteorological measurements aloft to better characterize atmospheric processes in the Tahoe Basin and enhance the data analyses and interpretations. LTADS thus collected a spatially and seasonally comprehensive database of atmospheric (air quality and meteorological) data which staff was unable to fully analyze and utilize in the preparation of this report. The LTADS approach provided estimates of dry deposition by a different method than previously used, confirming the N deposition estimate, refining the P deposition estimate, and providing a new PM deposition estimate. The estimates are based on observations representing the seasonal and diurnal variability of ambient concentrations and deposition velocities were calculated from hourly observations of meteorology and water temperature. In addition, to deposition estimates, the LTADS data allow important insights into probable sources of atmospheric deposition to the Lake. LTADS improved the understanding of many atmospheric issues relevant to development of the water clarity TMDL, but many issues may require further study. Staff summarized their LTADS efforts and participated in a forum to guide future research at a workshop in December of 2005. Presentations from this workshop are available on ARB's LTADS website (<http://www.arb.ca.gov/research/ltads/ltads.htm>).

ARB staff has also worked with the State Water Resources Control Board to sponsor a joint workshop on Atmospheric Deposition and Water Quality in February of 2006. Staff shared their insights and the presentations of this workshop are available on the State Water Resources Control Board's website (http://www.swrcb.ca.gov/workshops/atmos_pres.html). The ARB staff continues to work with the State and local Water Boards regarding the role of air pollution in additional water quality concerns.