

5. Annual Dry Deposition Estimates

5.1 Purpose

This chapter describes how the observed concentrations and calculated deposition velocities representative of specific locations and periods were interpreted to estimate spatially and temporally averaged annual dry deposition to the surface of Lake Tahoe. It presumes familiarity with the overview, provided in Chapter 2, of the methods and assumptions by which observed concentrations and calculated deposition velocities were summarized and combined to estimate the rates of dry deposition to the surface of Lake Tahoe. It provides additional detail on the interpretation of the concentration measurements described in Chapter 3 and the calculated deposition velocities that were derived from the relevant meteorological variables described in Chapter 4.

Wet deposition is also important as an input to the Lake, but was not a major focus of the LTADS field study for a number of reasons. LTADS did not emphasize observations of wet deposition because, with proper siting and care in sampling, observed wet deposition to surrogate surfaces may be used to infer wet deposition to the Lake. To provide the estimate of total atmospheric deposition to Lake Tahoe that is needed as input for the water clarity model, we do provide “back-of-the envelope” concentration-based estimates of the wet deposition and contrast with existing estimates based on observed wet/dry/bulk deposition to surrogate surfaces. Note that in this document references to deposition should be understood implicitly to refer to dry deposition unless there is an explicit reference to wet deposition.

5.2 General Methodology for Dry Deposition Estimates

The rate of deposition for any species for any particular period (e.g., a particular hour) can be calculated as the product of an observed ambient concentration and a deposition velocity representative of the meteorological conditions, surface characteristics and the chemical and physical properties of the species of interest. The annual deposition is the sum of those products (of ambient concentrations and calculated deposition velocities) integrated over time.

As discussed previously, ambient concentrations (C) and deposition velocities (V_d) vary temporally, spatially, and by pollutant. However, for each period and species, the basic deposition calculation remains the same:

$$\text{Dry Deposition Flux (F)} = C \times V_d.$$

The dry deposition estimates presented in this section correspond to a moderately sophisticated approach, where seasonal diurnal concentration profiles for the species of interest were merged with hourly deposition velocities calculated from hourly meteorological data.

5.3 Temporal Variation in Dry Deposition Rates

It is expected that for most species there is covariance of concentration and dry deposition velocity because both are influenced by common meteorological drivers. Thus, before attempting to calculate their product each should be represented with sufficient temporal resolution to capture their essential variation (unless for a particular case it can be demonstrated or reasonably assumed that there is either only minor temporal variation or very little covariance). The meteorological variables were continuously measured by standard methods and hourly averages of those meteorological variables capture the essential temporal variation. For most of the chemical species of interest to deposition at Lake Tahoe (including the gases - HNO_3 and NH_3 and the PM constituents - NO_3^- , NH_4^+ , and phosphorus) direct measurement of hourly concentrations is not possible. Although the time integrated filter samples collected with the TWS and mini-vols provide chemical speciation information for the composition of particles, they do not provide information on their diurnal variation. Thus, it was necessary to infer the diurnal variation in concentrations.

For each hour of the year, for which site-specific meteorological data was available, and for each species of interest, hourly deposition velocities were paired with a corresponding seasonally representative hourly concentrations to calculate an hour-specific dry deposition rate.

Thus, the conceptual model of seasonal concentrations was merged with seasonally averaged observed diurnal concentration patterns. Finally, deposition calculations merged the idealized diurnally and chemically-resolved air quality with diurnal patterns of air flow and deposition velocity derived from the meteorological data to generate a realistic chemically-resolved deposition estimate. Thus, for each species it was necessary to determine seasonal average concentrations and to estimate the daily variation associated with time of day that would arise from variation in emissions activity and meteorology.

Although hourly concentrations were not directly observed for each chemical species for each individual hour, it was possible to calculate seasonally representative hourly ambient concentrations for each of the physical state/variable combinations based on certain assumptions that are outlined in the following section.

5.3 Concentration Profiles

To generate an idealized diurnally and chemically-resolved picture of air quality at a monitoring site, the two week sampler (TWS) data were interpreted into a "conceptual model" that describes the mean air quality observed in each season. The seasons were defined as winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November).

Seasonal average concentrations were characterized for each of the following combinations of physical states and variables of interest:

- gas_HNO₃, gas_NH₃,
- PM2.5_mass, PM2.5_NO₃⁻, PM2.5_NH₄⁺, PM2.5_phosphorus,
- PM10_mass, PM10_NO₃⁻, PM10_NH₄⁺, PM10_phosphorus,
- TSP_mass, TSP_NO₃⁻, TSP_NH₄⁺, TSP_phosphorus,
- PM_coarse_mass, PM_coarse_NO₃⁻, PM_coarse_NH₄⁺, PM_coarse_phosphorus,
- PM_large_mass, PM_large_NO₃⁻, PM_large_NH₄⁺, PM_large_phosphorus.

PM_coarse and PM_large are not directly measured but are calculated from the measured TSP, PM10 and PM2.5 concentrations. PM_coarse, representing PM of diameter 2.5 < Dp < 10 microns, was defined as the difference in observed concentrations of PM10 and PM2.5. Similarly PM_large, representing the mass for PM with Dp > 10 microns, was defined as the difference in observed concentrations of TSP and PM10. The calculations of dry deposition assume that all phosphorus is in the particle phase. There were no measurements of gas phase phosphorus.

For most chemical species which occurred in a particle size cut it was assumed that their concentrations varied with that particle mass in the same diurnal pattern – i.e., that most chemical species of interest were a constant percent of particle mass. Subject to this assumption the hourly mass observations from the BAMs were used to represent the hourly variation in the chemical species contained in each size cut. Thus, it was possible to infer representative hourly concentrations for each of the particle species of interest, for each season, at each monitoring site.

For considering the diurnal (hour-to-hour) variation in concentrations of constituents of PM2.5 the following conventions were adopted. On a seasonal average, the concentrations of PM2.5_mass, PM2.5_phosphorus, PM2.5_NO₃⁻, and PM2.5_NH₄⁺ were assumed to vary diurnally (hour-to-hour) in the same manner that the PM2.5_mass varies (and as was measured with the BAM2.5).

For PM_coarse and PM_large the diurnal variations of PM_mass and PM_phosphorus were treated similarly, but the estimation of diurnal variation of the NO₃⁻ and NH₄⁺ in coarse and large PM differed. It was assumed that the hour-to-hour variations in total mass concentration and in phosphorus concentration were adequately represented (on a seasonal average) by the BAMs observations of PM_coarse and PM_large mass. That is, when averaged for each season, the observed concentration difference (BAM10 – BAM2.5) for each hour of day was assumed to represent the hour-to-hour variation in mass and phosphorus content of PM_coarse and (BAMTSP – BAM10) the variation in PM_large mass and phosphorus.

The concentrations of PM2.5_NO₃⁻, and PM2.5_NH₄⁺ were assumed to vary diurnally, on a seasonal average, in the same manner as the PM2.5_mass (as measured with the BAM2.5). The diurnal variation in the PM2.5 mass was relatively small and not important to the calculation, but the diurnal variation in the mass of PM with Dp > 2.5 was more pronounced.

Measurement precision did not permit reliable definition of the small differences in the concentrations of NO_3^- and NH_4^+ contained in TSP versus PM10 so an additional assumption was adopted for calculating diurnal variation of the concentrations of PM_NO_3^- and PM_NH_4^+ for particles larger than $2.5\ \mu\text{m}$. The seasonal average concentrations of NO_3^- and NH_4^+ in particles larger than $2.5\ \mu\text{m}$ were assumed to vary with hour of day in the same manner as the mass of particles larger than $\text{PM}_{2.5}$ as summed for all sizes instead of differentiating between PM_coarse and PM_large . Thus the concentrations in the two size categories (PM_coarse and PM_large) were aggregated and the seasonal variation in their sum was assumed to represent the variation in each of the individual size categories. Similarly the hourly variation in the aggregation of PM_coarse and PM_large was assumed to represent the diurnal variation in both PM_coarse NH_4^+ and PM_large NH_4^+ . Specifically, the hourly BAM observations of mass were seasonally averaged and ratios of the hourly concentrations to the seasonal average were calculated $[(\text{PM_coarse} + \text{PM_large})/(\text{the seasonal average of } \text{PM_coarse} + \text{PM_large for all hours})]$. Thus 24 hourly ratios were calculated for each season and for each site. Each ratio was applied as a multiplier for the appropriate hour to modulate the seasonal average concentrations of NO_3^- and NH_4^+ as measured in particles larger than $2.5\ \mu\text{m}$. For the deposition calculation it was arbitrarily assumed that the masses of NO_3^- and NH_4^+ found in all particles greater than $2.5\ \mu\text{m}$, were distributed 80% and 20% between PM_coarse and PM_large fractions.

The emission sources (primarily combustion related) that generate fine particles ($\text{PM}_{2.5}$) differ from those that generate coarse and large particles. Conversely, the sources that generate coarse and large particles are similar. Thus it is reasonable to treat the diurnal variation in fine particles separately from that of coarse and large particles. Similarly it is reasonable to treat the variation in coarse and large particles in the aggregate. In any case these assumptions have only small influences on the estimate of total dry deposition of nitrogen because the majority of the mass of ambient nitrogen and its deposition is in the gaseous species and not the PM.

Seasonally averaged hourly concentrations of HNO_3 were estimated based on concentrations of related gases that were measured hourly at Sandy Way. In the absence of similar measurements at other areas of Tahoe, the inferred diurnal pattern of HNO_3 concentrations at Sandy Way was assumed to be a reasonable representation for the diurnal pattern of HNO_3 near the Lake shoreline in general. Each area is subject to a similarly repetitive daily pattern of upslope/downslope wind flow and the primary human activities that generate emissions (e.g., transportation, housing, home heating, construction, etc.) are similarly proximate to the lakeshore. Although the concentrations will differ due to differences in emissions density, the similarity of meteorological patterns and spatial distribution of human activity proximate to the Lake, an assumption of similarity in the diurnal variation of HNO_3 concentrations is reasonable.

Observations of the hourly variability of NH_3 concentrations are generally not available, particularly at Lake Tahoe. For the purpose of calculating the deposition rate it was assumed that the concentrations of NH_3 did not vary appreciably with hour of day. The

ubiquitous NH_3 observed at the surface sites and aloft suggest that this assumption is not unreasonable.

5.4 Treatment of Deposition Velocity

The primary meteorological drivers for deposition velocity were wind direction, wind speed, and the air-water temperature difference. Three categories of wind direction were calculated at each monitoring site—onshore, offshore, and sideshore. Sideshore was defined as within 20 degrees of parallel to the shoreline. The wind direction is a factor in the near shore zone because there the upwind aerodynamic roughness changes markedly with wind direction. The aerodynamic roughness is characteristic of forest during offshore flow but characteristic of open water during onshore flow. Based on observations by Sun (2001) and lower wind speeds at Lake Tahoe we assume that the onshore roughness characteristics do not affect the atmospheric turbulence at distances of more than a kilometer from shore. Over open water the aerodynamic roughness is a function of wind speed and to a lesser extent air-water temperature difference due to wind generation of waves on the Lake. Thus, over open-water areas more than one kilometer from shore the wind direction is not a factor in the calculation of deposition velocity. For most hours the observed winds were either onshore or offshore, but for those hours of sideshore winds the effect on atmospheric turbulence was evaluated by taking a simple average of the aerodynamic resistances as calculated with the aerodynamic roughnesses for forest and mid-lake open water.

The deposition velocity for soluble gases (HNO_3 and NH_3) was estimated as $1/R_a$, assuming that $R_b \ll R_a$, ensuring that $R_{\text{total}} (=R_a + R_b + R_c)$ would not be underestimated. However, for some hours during downslope flow the value for R_a in the nearshore zone was very small resulting in unreasonably large calculated values for deposition velocity. Although it did not greatly influence the estimates of annual deposition of gases to the Lake, three alternative calculations were made. The calculated deposition velocity for gases (or $1/R_a$) was either allowed to become unrealistically large (10 cm/s) or it was constrained to a maximum value of either 3 or 6 cm/s. These treatments are referred to as “cap 10”, “cap 3”, or “cap 6”. The aerodynamic resistance and the cap values are common to calculation of deposition velocity for both gases and particles. The capping assumptions for aerodynamic resistance had less influence on the deposition velocity estimates for particles because those results depend not only on R_a , but also upon the explicitly calculated quasi-laminar layer resistance and the gravitational settling velocity as discussed in Chapter 4. The specific “cap” values selected to set the maximum allowable deposition velocity for gases were selected based on literature reports that the maximum observed deposition velocities for SO_2 over water are in the range of 3-4.5 cm/s. Deposition rates over water for SO_2 , HNO_3 or NH_3 are expected to be similar. Like HNO_3 and NH_3 , the surface resistance for deposition of SO_2 to water can be assumed to be zero. Thus, the deposition rate for each gaseous species depends primarily on R_a (which is entirely independent of chemical species) and only weakly on R_b (which is influenced primarily by environmental variables and only very weakly by molecular weight). Current

instruments are capable of measuring SO₂ with high temporal resolution and the deposition rate for SO₂ has been investigated extensively, including with direct measurements by the eddy covariance method. Again, it should be noted that the estimate of total deposition to the Lake is fairly insensitive to the selection of the capping value for the deposition velocity of the gases. It is invoked for only a fraction of the hours and only within the near-shore zone. For the purpose of the calculations the near shore zone was assumed to be 20 percent of the total area of the Lake.

The range of estimated annual deposition depends in part on assumptions about the relative distribution of particle mass between particle size categories and the distribution of mass within the size categories. Generally the measured concentrations define the distribution between the size categories. However, the assumed distribution of mass within each size category is also important. In making the estimates those assumptions are implied in selection of a representative particle diameter for each size category. Conservative judgements regarding representative particle diameters for PM_{2.5}, PM_{coarse}, and PM_{large} were made in order to avoid under estimating deposition rates.

For particles within size categories PM_{coarse} or PM_{large} the deposition velocity increases with particle size. Also, within these sizes, the particle mass is usually strongly dominated by that of the larger particles. For example, an appropriate deposition velocity for the PM_{coarse} would be predicted by assuming a representative particle of diameter of less than 10 microns. However, a particle diameter equal to the midpoint of the PM_{coarse} size range (6.25 μm) would likely cause underestimation of the deposition velocity and deposition rate because of the greater mass influence of larger particles. Because the upper bound deposition estimates assumed the extreme particle diameters of 2.5, 10 and 25 microns for PM_{2.5}, PM_{coarse}, and PM_{large}, the results are expected to over-estimate the actual deposition velocities and thus the deposition rates for each size fraction.

In the absence of definitive information on the size distribution of phosphorus, bounding estimates of the distribution between the size categories were made to avoid any underestimation of the deposition rate. As an upper limit a concentration of 40 ng/m³ was assumed over all areas of the Lake at all times. This was apportioned as 20 percent PM_{2.5}, 60 percent PM_{coarse}, and 20 percent PM_{large} (i.e., 8, 24 and 8 ng/m³). In particular the assumption of 8 ng/m³ of phosphorus within the PM_{large} fraction, applied over all areas of the Lake surface with a deposition velocity calculated for a particle size of 25 microns is expected to provide a conservative upper bound on the phosphorus deposition rate.

5.5 Spatial Averaging

To provide a spatial average, the annual average deposition rate to the lake surface was calculated as the simple average of the annual deposition rates calculated from each of four air quality quadrants representing approximately equal areas of the Lake (Figure 5-1). The quadrants were chosen based upon observed similarity in meteorological conditions and density of human population and human activities that

may be related to emissions. The differences in observed concentrations at the various sites are generally congruent with the differences in population density and traffic near those sites. It should be noted that the concentration measurements used in the deposition estimates are all land-based and most are near emission sources. The extrapolation of these concentrations over the lake and no consideration of reduction due to dispersion and deposition generates a conservative (i.e., upper limit) estimate of deposition to the Lake surface. Because the strength of the upslope and downslope flows was observed to be approximately proportional to the steepness of terrain, the relative steepness of terrain was also considered along with the observed winds and concentrations.

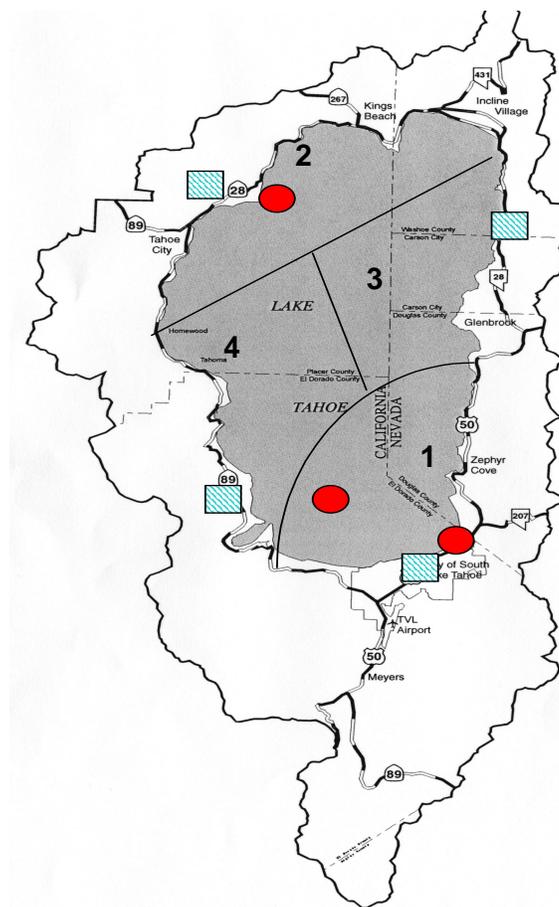


Figure 5-1. Lake quadrants used to calculate annual deposition.

Because the air-water temperature difference was an important part of the atmospheric stability calculations, only on-lake or pier sites featuring winds and both air and water temperatures in the vicinity of full air quality monitoring sites were used in the

calculations of deposition velocity. However, for hours when water temperature data was missing for a specific site the average of water temperatures observed at the other sites was used. Meteorological data from U.S. Coast Guard (USCG) Pier provided the most complete data record for the entire year. A comparison of seasonally average deposition velocities based on meteorological data from different sites showed relatively small spatial differences as would be expected based on the importance of the land-lake breeze at all sites. Thus, the deposition velocities based on meteorological data from U.S. Coast Guard Pier were used for the E/NE and W/SW quadrants of the Lake. For the purposes of a lake-wide estimate concentrations for the NE and SW quadrants were assumed to be 33% of the PM mass and 58% of the gaseous and aerosol nitrogen observed at Lake Forest. These concentrations are based on a preliminary review of the air quality data. A refined analysis, currently underway, will yield improved estimates of concentrations for these quadrants.

Thus, in summary the quadrants (depicted in Figure 5-1), which were chosen based on air quality measurements and population/ activity densities, are:

- Quadrant 1: S & SE Lake – meteorological data from Timber Cove (TC) and a southern buoy (TDR2) and concentration data from the South Lake Tahoe - Sandy Way site (SW) were used to calculate deposition estimates for this sector of Lake Tahoe.
- Quadrant 2: N & NW Lake – For this area, meteorological data from U.S. Coast Guard (USCG) Pier and concentration data from Lake Forest (LF) were used to calculate deposition estimates for this sector of Lake Tahoe.
- Quadrant 3: E & NE Lake and Quadrant 4: W & SW Lake - Concentrations for these two quadrants were assumed to be 33% of the PM mass and 58% of the gaseous and aerosol nitrogen observed at Lake Forest.

5.6 Annual Deposition Rates

A best estimate of the annual atmospheric dry deposition of N, P, and PM to Lake Tahoe and conservative upper and lower bound estimates are presented below, based on the methods presented in this chapter and the key assumptions discussed previously and summarized in the companion table.

Table 5-1 LTADS Estimate of Dry Atmospheric Deposition of N, P, & PM to Lake Tahoe
(metric tons/year)

Pollutant	Lower Estimate	Best Estimate	Upper Estimate
N (NH ₃ , NH ₄ ⁺ , HNO ₃ , NO ₃ ⁻)	110	160	230
P (P, PO ₄ ⁻³)	0.7	1	6
PM (fine, coarse, large)	850	1300	1800

Table 5-2 Assumptions Used to Generate Lower, Best and Upper Estimates

Assumptions	Lower Estimate	Best Estimate	Upper Estimate
Maximum of 1/ R _a for particles and gases (cm/s)	3	6	10
Characteristic particle diameter of PM _{2.5} , coarse, large	1, 5, 15	2, 8, 20	2.5, 10, 25
% distribution of phosphorus mass in PM-2.5, coarse, large	20-80-0	20-60-20	20-60-20
Phosphorus Concentration (ng/m ³)	10	20	40

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