5. Wet Atmospheric Deposition

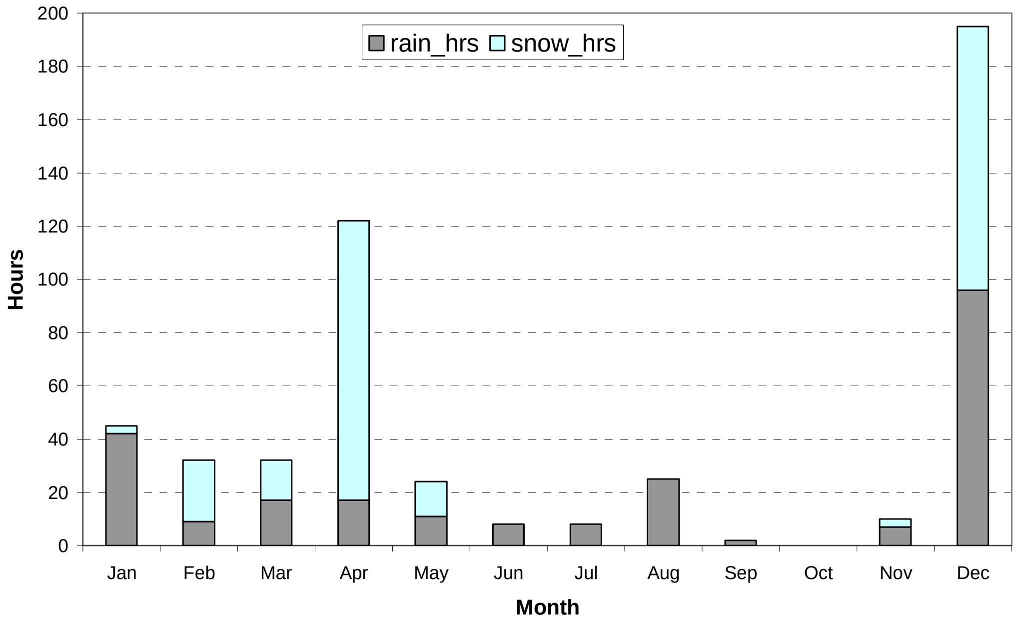
5.1 Introduction

Historical wet/dry deposition measurements with bucket samplers indicate that wet deposition is a major component of the total annual atmospheric deposition to Lake Tahoe (Jassby, et al., 1994). Wet deposition removes nitrogen, phosphorus, and particulate matter from the air via two main processes: nucleation scavenging and impaction scavenging. Nucleation scavenging occurs when particles act as cloud condensation nuclei. As water accumulates on the particle, the aerosol may increase in size until the cloud (fog) droplets deposit on surfaces or fall out of the air as precipitation. Impaction scavenging occurs when precipitation removes aerosols by physical contact (or absorption in the case of water-soluble gases such as ammonia and nitric acid) with the much larger water droplet or snowflake. Because snowflakes have a much larger surface area than a raindrop and more than half of the annual precipitation hours in the Tahoe Basin occurs as snow (**Figure 5-1**), wet deposition by snowfall is a significant component of the total atmospheric deposition in the Tahoe Basin. Most of the total annual precipitation in the Tahoe Basin occurs during the winter and spring (see **Figure 2-3**).

Wet deposition measurements (besides those routinely collected by the Tahoe Research Group) were not a component of the LTADS field study. However, CARB staff estimated wet deposition onto Lake Tahoe during 2003 based on a simple analysis of seasonal air quality concentrations from the TWS network and the associated seasonal number of hours when precipitation fell. This analysis was necessary to develop total annual PM deposition estimates as the conventional wet deposition measurements with a surrogate surface do not make particulate matter (PM) measurements. The assumption is that, if the simple wet deposition model applied here reasonably reproduces the wet deposition estimates of N and P with the surrogate surfaces (deemed to be accurate), then the wet deposition estimate for PM is more likely to be reasonably accurate.

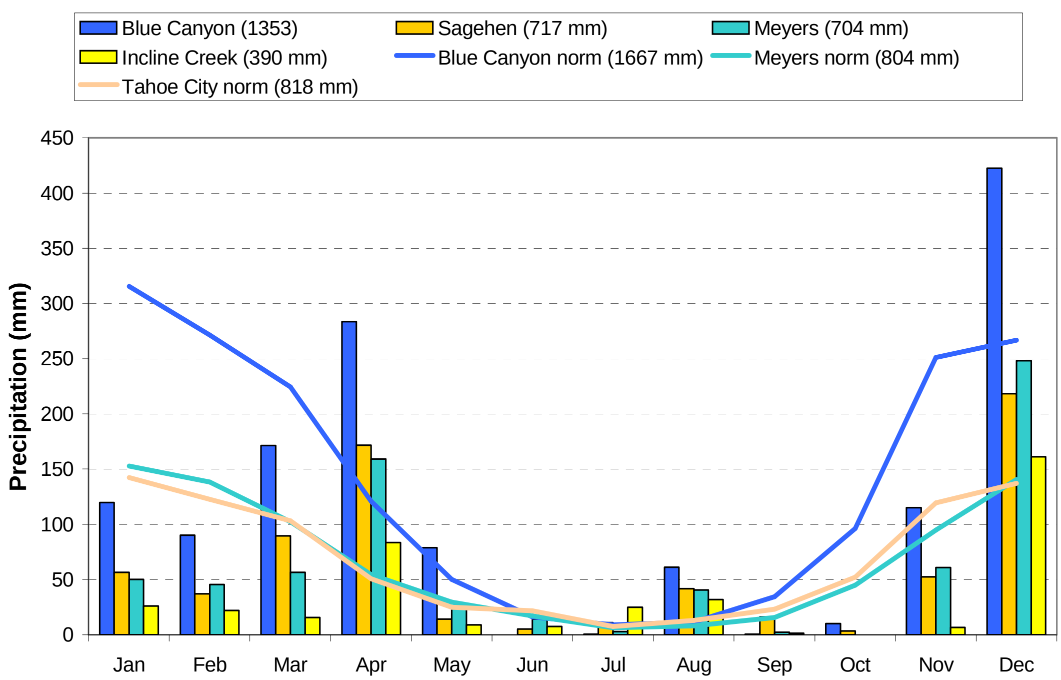
Precipitation amounts in the northern Sierra Nevada during 2003 were less than normal with only the months of April, August, and December being wetter than normal (**Figure 5-2a**). On a seasonal basis (i.e., winter – January, February, and December; spring – March through May; summer – June through August; and fall – September through November) and focusing on the long-term monitoring site in Meyers, CA (located near to and southwest of South Lake Tahoe), precipitation amounts in the Tahoe Basin in 2003 was about 25% below normal in winter, 25% above normal in spring, slightly above normal in summer, and about 50% below normal in fall (**Figure 5-2b**).

Figure 5-1. Estimated proportion of rain and snow observed in precipitation at Incline Creek, 2003.



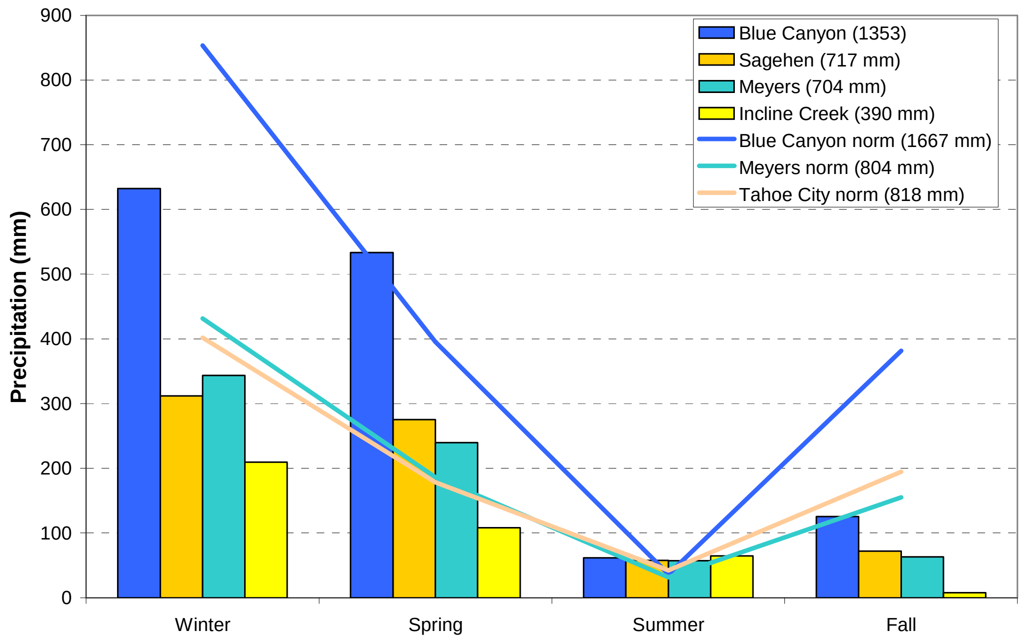
Note: the number of snow and rain hours is based on the air temperature at ground level relative to 0 ^{O}C when precipitation was reported; actual snow hours would be greater because cloud temperatures are colder than the ground-level temperature.

Figure 5-2a. Monthly precipitation in 2003 (bars) compared to long-term means (lines).



Note: Blue Canyon is located west of the Sierra Nevada crest; Sagehen is located east of the Sierra crest but northwest of the Tahoe Basin; Meyers is located in the southern Tahoe Basin; Incline Creek is located in the northeastern Tahoe Basin; and Tahoe city is located on the northwestern shore of Lake Tahoe.

Figure 5-2b. Seasonal precipitation in 2003 (bars) compared to long-term means (lines). The annual precipitation totals for 2003 and long-term means are shown in the legend box.

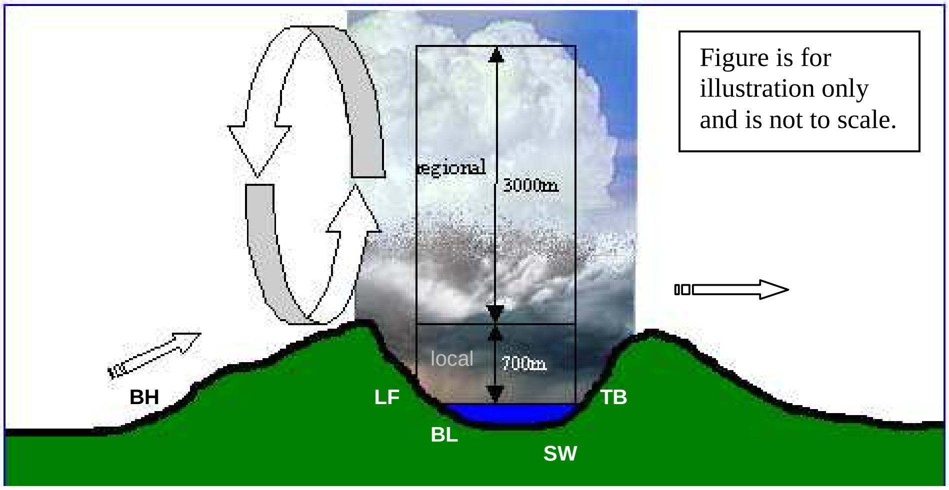


5.2 Conceptual Model of Wet Deposition

The wet deposition loading of a pollutant is estimated from the mass of that pollutant in a "cylinder" above the Lake, and the frequency and efficiency with which that air volume is cleansed by precipitation. The mass of a pollutant in the air above the Lake in each season is estimated by multiplying the seasonally and spatially representative ambient concentration of each pollutant by the volume of air (surface area of Lake Tahoe times the depth of the cylinder being cleansed by precipitation). The annual wet deposition loading is then the sum of these seasonal masses times the number of precipitation events during each associated season.

The wet deposition analysis was divided into two components addressing locally-generated pollutants and transported (regional background) pollutants (**Figure 5-3**). Conceptually, the local component is represented by the removal of pollutants over Lake Tahoe (based on measurements near the shoreline) and extending 700 meters from the Lake's surface up to a representative altitude of the crest of the surrounding mountains (i.e., local pollutants are trapped in the Tahoe Basin by the mountains surrounding the Lake or are advected out of the Basin if they rise higher). In a similar manner, the transport component of the wet deposition is represented by the washout of regional pollutants in a layer of air extending 3000 meters above the mountain crests (i.e., the air of regional origin that passes over the Tahoe Basin).

Figure 5-3. Conceptual model of regional and local components of wet deposition estimate to Lake Tahoe. (BH – Big Hill, LF – Lake Forest, BL – Bliss State Park, SW – SLT-Sandy Way, TB – Thunderbird Lodge)



As regional airflow carries pollutants up the western slope of the Sierra, they are mixed through a deep layer during precipitation periods. Although thunderstorm tops in northern California typically reach 9000 m to 12,000 m (30,000 to 40,000 feet) MSL, the depths of the storms are generally about 6000 m to 9000 m (20,000 to 30,000 feet), with even shallower storms common during the winter (NWS, 2003). Vertical mixing in the atmosphere is not as deep during non-storm conditions as indicated in **Figure 5-4**, which shows summer pollutant profiles above Big Hill as measured by an airplane. Even so, most of the pollutant emissions, although originating near ground level, mix upward (more than 1000 m) due to solar heating on the western slope of the Sierra. This mixing of pollutants may extend up to the base of the subsidence inversion frequently observed during summer around 3,000 m MSL (10,000 – 11,000 feet) or 300 – 600 m above the crest of the Sierra Nevada. The atmospheric mixing associated with storms (instability) would mix these pollutants up through a deeper layer (i.e., the depth of the storm cloud or about 6000 m). Thus, the surface-based pollutant concentration measurements at Big Hill are representative of the average pollutant concentrations in a relatively deep layer of air (1000 – 1500 m during stable periods and 6000 m or more during storms. Staff assumed that the average pollutant concentration throughout the storm layer would be about ½ of the measurement at ground level at Big Hill. The equivalent formulation in the wet deposition model is to represent the mass of material available for removal as wet deposition as $[AQ]_{BH}$ x 3000m, rather than ½ x $[AQ]_{BH}$ x 6000 m. Thus, the transport (regional) component of wet deposition is represented by the washout of the regional pollutant concentrations characterized by conditions at Big Hill in a 3000 m layer of air above the crest of the Sierra Nevada.

The local component is represented by local pollutant concentrations (i.e., the Tahoe 4-quadrant average) in a 700 m layer of air extending from the Lake's surface to the height of the Sierra crest. These regional and local concentrations in the upper and lower sections of a cylinder above the Lake (separated at the height of the Sierra Nevada) were characterized seasonally and represent the pollutant loadings potentially available for wet deposition to the Lake. The actual amount of wet deposition is determined by the seasonal frequency of precipitation removing the pollution.

The wet deposition calculations used ground level, ambient pollutant concentrations observed by the TWS network during the cleanest (representative) 2-week measurement period during winter and spring to represent the cleaner air quality associated with organized (frontal) precipitation periods. Because precipitation does not constantly occur during a 2-week period, the use of the minimum 2-week concentrations likely overestimates the actual concentrations during storms. For summer and fall when precipitation events consist of scattered showers, seasonal mean ambient concentrations were used. Under typical dry conditions, pollutant concentrations begin to decline with increasing altitude due to dispersion of primarily ground-based emissions and mixing with typically cleaner air found aloft. However, during a thunderstorm, deep vertical mixing occurs and the ambient pollutant concentrations are smaller and not likely to decline as rapidly with altitude (i.e., similar amount of total pollutant mass but distributed through a deeper layer of air than what occurs under dry conditions). Thus, the seasonal mean is the best estimate of the air quality in the column of air when isolated showers develop.

Figure 5-4a. Data from a morning aircraft spiral above Big Hill on August 22, 2002, 0814-0830 PST.

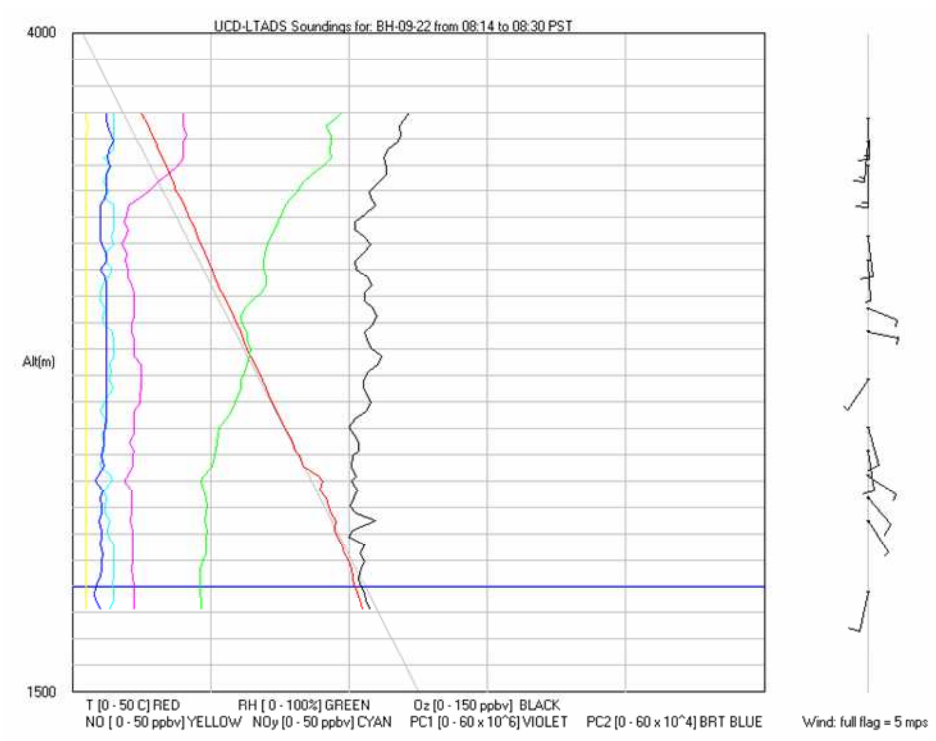
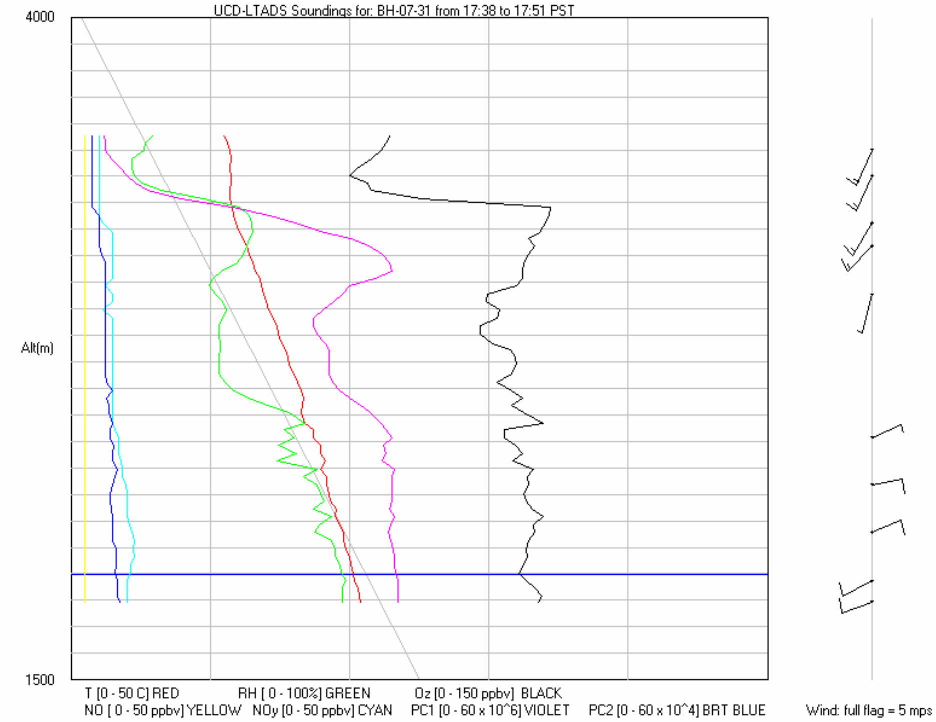


Figure 5-4b. Data from an afternoon aircraft spiral above Big Hill on July 31, 2002, 1738-1751 PST.



This wet deposition analysis uses precipitation data collected during 2003 at Incline Creek located near the northeast shore of Lake Tahoe. Precipitation in this portion of the Tahoe Basin is comparable to other monitoring sites in the region for frequency (**Figures 5-5a, c**) but below average for quantity (**Figures 5-5b, d**). Schumann et al. (1988) suggest that the bulk of the air pollution is removed during the beginning of the storm (precipitation) and Zinder et al. (1988) suggest that below-cloud removal can be efficient. Consequently, CARB staff believes that the frequency of precipitation events is a better indicator of the wet deposition of atmospheric pollutants than is the amount of precipitation. Thus, this analysis is based on the assumption that any precipitation, whether light or intense, will cleanse the air of pollutants. Byers (1965) suggests that an hundredth of an inch of rain in one hour will remove about 75% of the aerosol pollutants in the air.

Staff's analysis assumed that ambient pollutant concentrations were replenished every hour. This may be reasonable for regional transport and local gaseous and PM2.5 emissions but might not be for larger particles. Thus, the wet deposition analysis likely overestimates the actual deposition of PM. An alternative assumption might be that large particles of local origin are only regenerated on a daily basis rather than an hourly basis due to the time needed for generation (e.g., diurnal emission cycles, drier roads) and for particle growth. Based on the average precipitation frequency in 2003, which indicated about 5 hours of precipitation per day when precipitation occurred) and assuming that PM2.5 comprises ~50% of the total PM mass during the primary wet deposition seasons of winter and spring, this assumption (daily rather than hourly replenishment of PM_coarse and PM_large) would reduce the wet deposition estimates of PM to 60% of the deposition estimated on an hourly replenishment basis.

Figure 5-5a. Number of days with precipitation during 2003, by month.

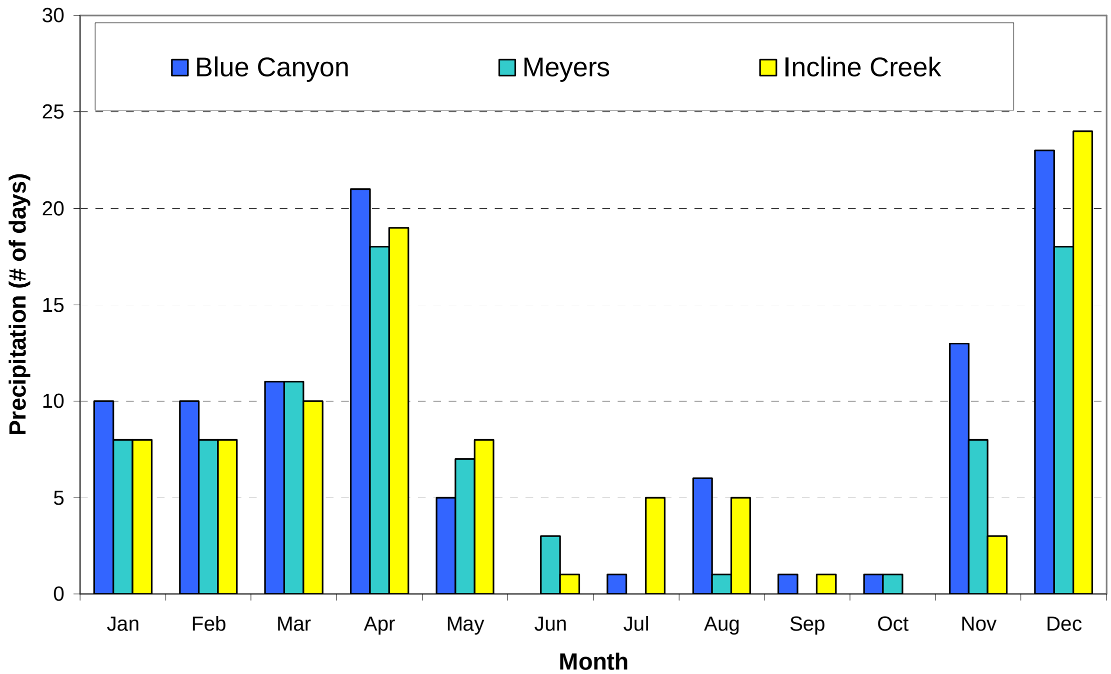


Figure 5-5b. Precipitation amounts during 2003, by month. Long-term normal annual precipitation totals are shown in parentheses.

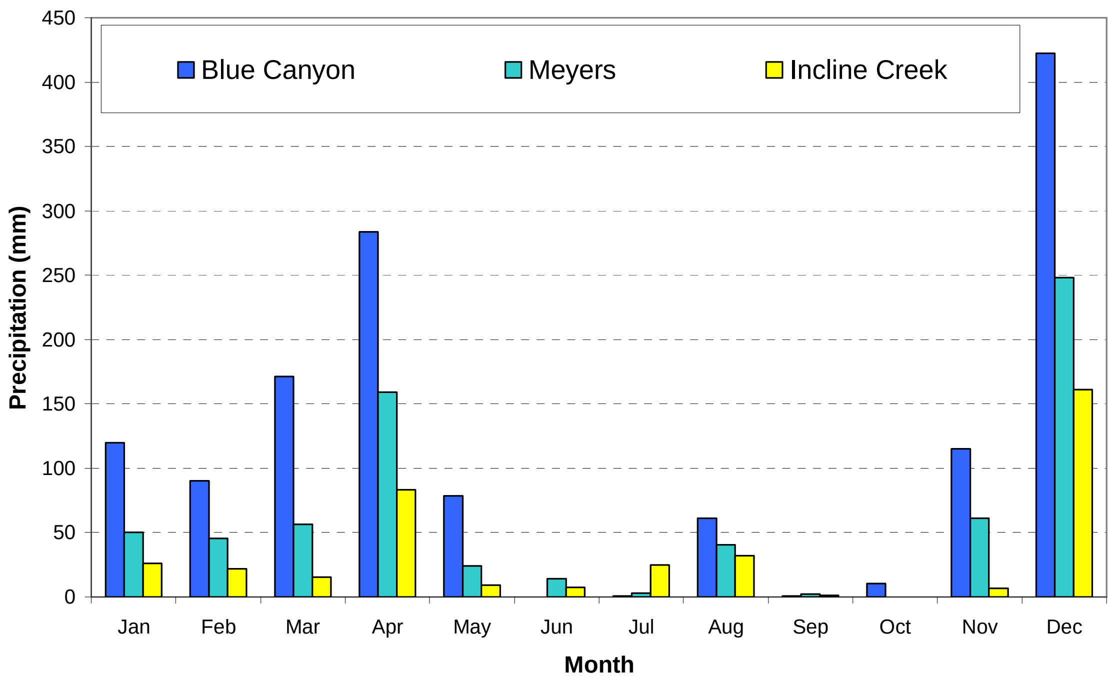


Figure 5-5c. Number of days with precipitation during 2003, by season.

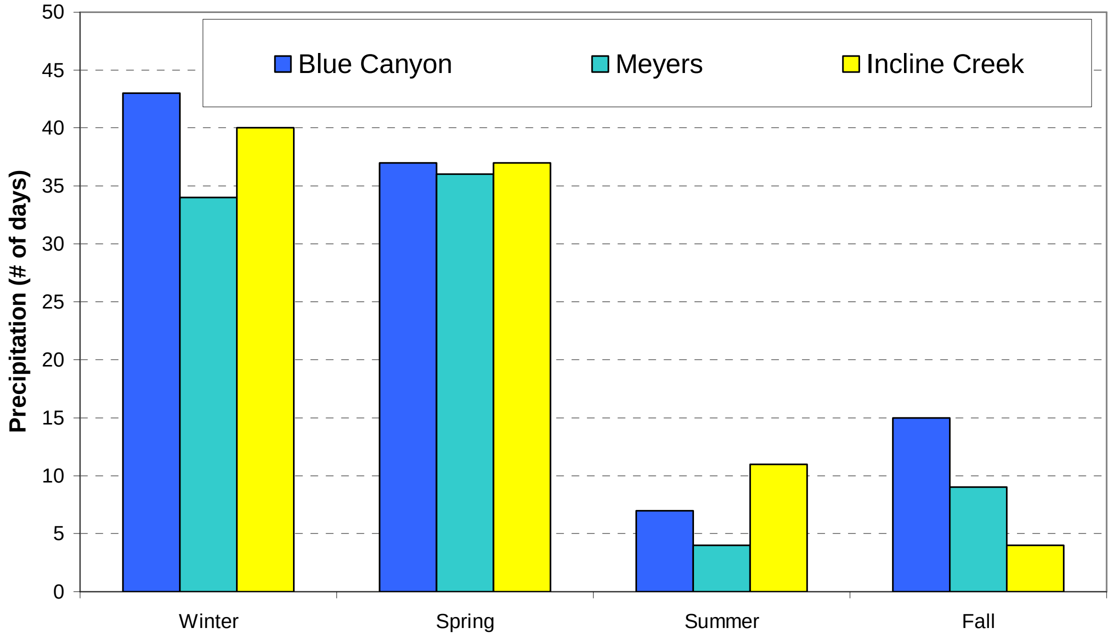
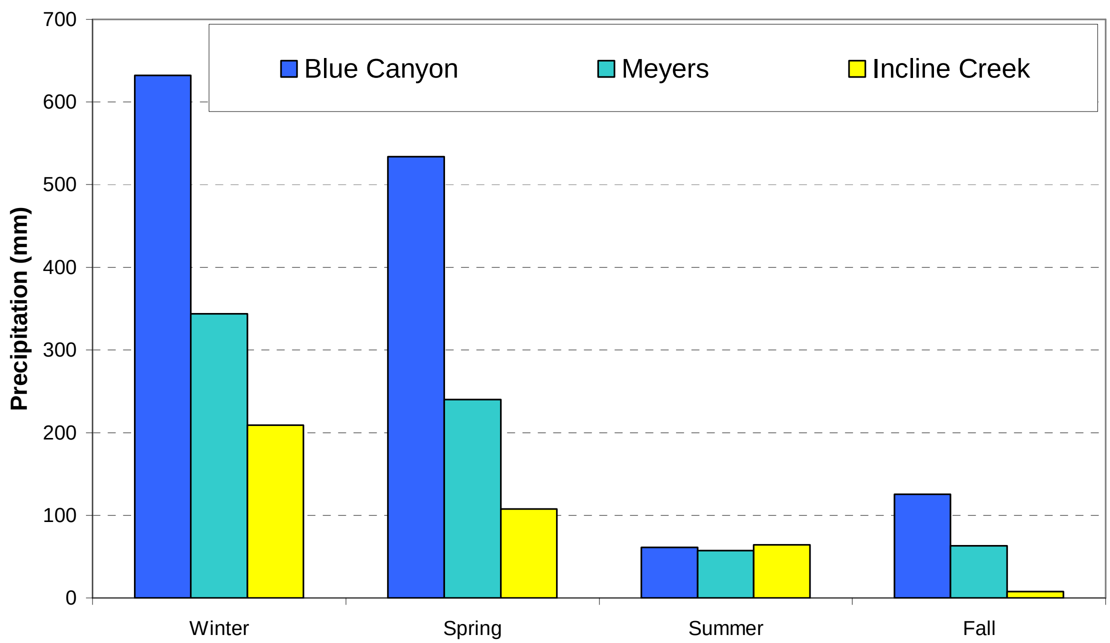


Figure 5-5d. Precipitation amounts during 2003, by season.



5.2.1 Wet Deposition from Regional Pollution Sources

The concentration of each pollutant in the transport layer is based on measurements during each season at Big Hill, the upwind regional air quality site (see Regional Source listing in **Table 5-1**). Because precipitation occurs differently in summer and fall (isolated showers) as compared to winter and spring (frontal systems), seasonal mean specie concentrations were used for summer and fall wet deposition estimates and the minimum 2-week average specie concentration observed during winter and spring were used for the winter and spring wet deposition estimates. Gaseous and aerosol pollutants are included in the conceptual wet deposition model. TSP and the associated species (NH_4^+ and NO_3^-) were used because: a) the enhanced vertical and horizontal air motion during storms could permit some large particles to traverse the Sierra Nevada and arrive at Lake Tahoe before depositing, and b) the PM method comparison indicated the TSP concentrations by the TWS may be biased low ~5 ug/m^3 (15-20%) compared to the other PM measurement methods. The following wet deposition calculations assume that the pollutant concentrations at Big Hill are well-mixed in a 3000 meter thick air layer above the crest of the Sierra Nevada due to the vigorous mixing during storms. Given that the typical thickness of a storm cloud in this region is about 6000 meters (NWSFO, 2003), this assumption is equivalent to saying that the average pollutant concentration throughout the 6000 m storm cloud is one-half the pollutant concentration at ground-level (i.e., the total mass available for deposition is the same).

As the air mass is transported over the Tahoe Basin, precipitation washes the regional pollutants out of the air. The Sierra Nevada enhances precipitation on its western slope and crest but the mountain range also creates a rain shadow downwind (east) of the crest. Considering long-term precipitation averages (along a line segment from Big Hill to Lake Tahoe) indicates that about 10 percent of a storm band's total precipitation (and presumably pollutant load), on average, falls onto Lake Tahoe as it travels from Big Hill, over the Sierra Nevada, and to Lake Tahoe (**Figure 5-5**). Given the limited air pollution sources between Big Hill and Lake Tahoe, about 10% of the pollutants embedded in the original air mass can actually fall onto Lake Tahoe. Furthermore, all of the pollutants that actually survive the trip to Tahoe are not necessarily washed out of the air by precipitation and various assumptions about pollutant wash-out efficiency must be made. The meteorological assumptions in the wet deposition estimates are summarized in **Table 5-2** and are described in more detail below.

Table 5-1. Seasonal air quality concentrations (from TWS network) used in estimating wet deposition to Lake Tahoe during 2003. Representative minimum 2-week pollutant concentrations were used for winter and spring while seasonal means were used for summer and fall.

Pollutant	Pollution Source	TWS Site	Seasonal Concentrations (ng/m^3)			
			winter	spring	summer	fall
Ammonia (NH_3)	regional	Big Hill	65	89	984	719
	local	SLT – Sandy Way	469	480	1043	1227
	local	Lake Forest	513	229	861	835
	local	Thunderbird Lodge*	11	40	298	277
Nitric Acid (HNO_3)	regional	Big Hill	87	99	1127	816
	local	SLT – Sandy Way	719	405	772	1294
	local	Lake Forest	111	140	564	647
	local	Thunderbird Lodge*	145	80	530	379
NO_3 (in TSP)	regional	Big Hill	177	617	1763	1394
	local	SLT – Sandy Way	774	629	1210	1155
	local	Lake Forest	279	341	657	617
	local	Thunderbird Lodge*	124	278	1014	577
NH_4 (in TSP)	regional	Big Hill	30	208	430	552
	local	SLT – Sandy Way	191	244	336	496
	local	Lake Forest	54	139	301	297
	local	Thunderbird Lodge*	65	127	289	287
P+	regional	Big Hill	27	26	30**	31**
	local	SLT – Sandy Way	17	28	40	40
	local	Lake Forest	9	32	40	40
	local	Thunderbird Lodge*	20	27	40	40
PM	regional	Big Hill	1586	3984	15,165	12,797
	local	SLT – Sandy Way	9274	10,674	14,654	21,339
	local	Lake Forest	5222	9277	14,756	15,138
	local	Thunderbird Lodge*	1650	2957	10,116	7760

* DL Bliss SP was not part of the TWS network but was the sampling site used to represent air quality in the SW quadrant of the basin. Limited LTADS sampling and long-term IMPROVE sampling at DL Bliss indicated low concentrations and similarity with TWS measurements at Thunderbird Lodge. For the purpose of estimating the mean concentrations of pollutants within the basin, staff assumed concentrations at Bliss were the same as at Thunderbird Lodge.

\+ [Phosphorus]s in winter and spring are 40 ng/m^3 times the seasonal ratios of $[TSP]_{2\text{-wk minimum}}/[TSP]_{mean}$.

** [P]s at Big Hill in summer and fall are 40 ng/m^3 times the seasonal ratios of [PM10]/[TSP] (assumes P in PM with diameter > 10 um does not transport over the ~25 miles to Lake Tahoe).

Table 5-1a. Size breakdown of seasonal particulate matter concentrations (from TWS network) used in estimating wet deposition to Lake Tahoe during 2003. Representative minimum 2-week pollutant concentrations were used for winter and spring while seasonal means were used for summer and fall.

Pollutant	Pollution Source	TWS Site	Seasonal Concentrations (ng/m^3)			
			winter	spring	summer	fall
PM_fine	regional	Big Hill	563	1905	6887	4962
	local	SLT – Sandy Way	6333	3771	5922	9772
	local	Lake Forest	1576	2016	6286	4506
	local	Thunderbird Lodge	1307	1786	5723	3745
PM_coarse	regional	Big Hill	344	1795	4855	4898
	local	SLT – Sandy Way	1837	4483	7000	7961
	local	Lake Forest	3640	7204	7761	9402
	local	Thunderbird Lodge	197	1111	3859	2575
PM_large	regional	Big Hill	678	284	3423	2938
	local	SLT – Sandy Way	1104	2420	1732	3606
	local	Lake Forest	8	57	719	1230
	local	Thunderbird Lodge	146	60	534	1440

Table 5-2. Meteorological assumptions for estimating wet deposition to Lake Tahoe in 2003.

Parameter (units) \ Season:	**Estimate Range**	**winter**	**spring**	**summer**	**fall**
MD - atmospheric mixing depth (meters)[1]	regional pollution	3000	3000	3000	3000
	local pollution	700	700	700	700
PF - precipitation frequency (hours/days)	lower bound[2]	184/30	120/28	28/8	8/3
	central estimate[3]	272/40	178/37	41/11	12/4
	upper bound[4]	374/50	245/46	56/14	17/5
(transport / local) fraction of precipitation that falls onto Lake Tahoe (%)[5]	lower bound	5 / 100	5 / 100	5 / 5	5 / 5
	central estimate	10 / 100	10 / 100	10 / 10	10 / 10
	upper bound	15 / 100	15 / 100	15 / 15	15 / 15
washout efficiency (%)	lower bound	50	50	50	50
	central estimate	75	75	75	75
	upper bound	100	100	100	100

[1] mixing depth layers are stacked with the "local" contribution on bottom (extending from the Lake surface at ~1900 m MSL to Basin ridgeline at ~2600 m MSL) and with the "regional" or "transport" contribution on the top (extending 6000 m from the Basin ridgeline at ~2600 m MSL to ~8600 m MSL). Because pollutant concentrations at Big Hill are well-mixed (at least through 1000 m during stable periods and 6000 m or more during unstable periods), concentrations at Big Hill were assumed to be representative of a well-mixed air layer 3000 m thick (i.e., ~2x the minimum mixing depth and ~½x the mixing depth during precipitation events). Any greater mixing would likely entrain "clean" air aloft. Because storms would increase mixing through a depth of 6000 m or more but not the mass of pollutants, the total transport mass available for wet deposition would remain the concentration at Big Hill times the area of Lake Tahoe times 3000 m. Similarly, the total local mass available for wet deposition is the 4-quadrant average local concentration times the area of Lake Tahoe times 700 m. Thus, the total depth of the cylinder above the Lake from which wet deposition was estimated is 3700 m.

[2] lower bound = includes 0.75 x central estimate of precipitation days and 0.90 x central estimate of hours of precipitation/day (i.e., 68% of number of precipitation hours in central estimate)

[3] central estimate = actual observation at Incline Creek during 2003

[4] upper bound = includes 1.25 x central estimate of precipitation days and 1.10 x central estimate of hours of precipitation/day (i.e., 138% of precipitation hours in central estimate)

[5] winter & spring feature organized storm systems while summer & fall feature scattered showers; winter & spring transport fraction based on west-to-east fraction of total precipitation between Big Hill and eastern shoreline of Lake Tahoe; summer & fall fractions based on fraction of lake surface experiencing shower (showers more likely to occur over land than lake).

The regional (transport) component of wet deposition is represented by:

WetDep_regional (metric tons) = $[\text{pollutant}]_{\text{Big Hill}}$ ***** MD ***** CF ***** PF ***** HW ***** VW, where:

$[\text{pollutant}]_{\text{Big Hill}}$ = the seasonal representative concentration of a particulate or gaseous pollutant at Big Hill in ng/m^3. With limited emission sources between Big Hill and Lake Tahoe, and assuming good atmospheric mixing by the time the polluted air mass arrives at Big Hill, concentrations at Big Hill are assumed to be reasonably representative of concentrations along Sierra Nevada west of Lake Tahoe and transported over Tahoe Basin). In the calculations for summer and fall when precipitation falls as scattered showers, the seasonal mean concentrations are used; for the winter and spring calculations when widespread precipitation is associated with frontal passages, the observed seasonal minimum 2-week-average concentrations are used.

MD = mixing depth (transportable pollutants measured at Big Hill were assumed to be mixed throughout 3000 meters above the crest of the Sierra Nevada),

CF = conversion factor of 5.01×10^{-7} (converts concentration units (ng/m^3) and surface area of Lake Tahoe to metric tons of pollutant per meter of altitude (i.e., mixing depth) available for wet deposition,

PF = precipitation frequency (varies with type of pollutant); specifically, the number of *hours* during each season with measurable precipitation for gases and secondary particulate matter; the number of *days* during each season with measurable precipitation for primary particulate matter, which includes phosphorus. This construct applies an assumption of rapid (hourly) replenishment of atmospheric concentrations for gases and secondary particles but slower (daily) replenishment of primary particles,

HW = horizontal washout or fraction of total precipitation falling on Lake Tahoe (i.e., during winter and spring when storm systems occur, the fraction of total precipitation falling between Big Hill and Lake Tahoe that falls onto Lake Tahoe; during summer and fall when precipitation occurs as scattered showers, the areal fraction of the Lake impacted by showers),

VW = vertical washout efficiency (i.e., fraction of total transported pollutant mass actually washed out of air column by precipitation)

The annual wet deposition due to regional sources of pollution is simply the sum of the seasonal, regional wet deposition estimates.

5.2.2 Wet Deposition from Local Pollution Sources

The local component of wet deposition is estimated in a manner similar to the regional component. Instead of a layer of air above the height of the Sierra Nevada, this layer of air with local pollutants extends from the Lake surface up to 700 meters (the base of the “transport” layer). Because the pollutants in this surface layer of air are close to their sources and are not mixed as well as in the transport layer, the average pollutant concentration in the local layer of air was estimated as the mean of the pollutant concentrations in four quadrants around the Lake. Thus, a regional mean of the seasonal minimum 2-week average pollutant concentrations measured near the shoreline in four quadrants of the Lake was assumed to extend from the Lake's surface up to 700 meters (approximate height of mountain ridgeline above the Lake) during winter and spring. For summer and fall wet deposition estimates, the seasonal mean concentrations were used. The basic equation representing wet deposition of local air pollution is:

WetDep_local (metric tons) = $[\text{pollutant}]_{\text{4-quad mean}}$ ***** MD ***** CF ***** PF ***** HW * VW, where:

[pollutant] = the regional concentrations of a particulate or gaseous pollutant in ng/m^3 (average pollutant concentrations from four sites characterizing four quadrants around the Lake); seasonal concentration means were used for summer and fall when scattered showers occur; seasonal minimum 2-week average concentrations were used during winter and spring when frontal storms occur,

MD = mixing depth (local pollutants were assumed to be mixed through 700 meters),

CF = conversion factor of 5.01×10^{-7} (converts concentration units (ng/m^3) and surface area of Lake Tahoe to metric tons of pollutant per meter of altitude (i.e., mixing depth) available for deposition,

PF = precipitation frequency (definition varies with pollutant type for the purpose of applying different rates of replenishment of atmospheric concentrations) i.e., the number of hours during season with measurable precipitation for gases and secondary particulate matter; the number of days during each season with measurable precipitation for primary particulate matter, which includes phosphorus,

HW = horizontal washout of fraction of Lake Tahoe impacted by precipitation (i.e., during winter and spring when storm systems occur, precipitation falls over the whole Lake and the HW=1; during summer and fall when precipitation occurs as scattered showers, the HW (areal fraction of Lake Tahoe Impacted by showers) varied among 0.05 for the Lower Bound, 0.10 for the Central Estimate, and 0.15 for the Upper Bound),

VW = vertical washout efficiency (i.e., fraction of local pollutants washed out of the local air layer by precipitation)

The annual wet deposition due to local sources of pollution is simply the sum of the seasonal, local wet deposition estimates.

5.2.3 Wet Deposition Assumptions

Many of the assumptions used in this analysis could be refined with additional review of meteorological data collected during LTADS or previously. A synopsis of the model parameters and the associated assumptions is presented below.

Pollutant Concentrations – To generate seasonal estimates of wet deposition, seasonal pollutant concentrations were input. Except for the DL Bliss State Park data, which were estimated and not directly measured, the lowest representative 2-week mean concentration for each pollutant (based on data from the TWS network) were input for each site for the winter and spring seasons and seasonal mean concentrations were input for the summer and fall seasons. Because precipitation does not occur continuously during the summer and fall or even for two weeks during the winter and spring seasons, these concentrations (and the subsequent wet deposition estimates) may be biased high to some extent. Because the air quality in the Bliss quadrant of the basin is normally good, the effect of the assumptions for the Bliss site is generally minor. In addition, P concentrations were only infrequently quantifiable during LTADS. In the dry deposition estimates, staff assumed [P]s of 40 ng/m^3 based on the limited number of phosphorus detections during LTADS, measurement uncertainties, and assumed corrections. To characterize phosphorus concentrations during the frontal storm precipitation periods (i.e., winter and spring), the [P]s (fixed at 40 ng/m^3) during winter and spring were multiplied by the seasonal ratios of $[TSP]_{2\text{-week minimum}}/[TSP]_{\text{seasonal mean}}$. The 40 ng/m^3 [P]s during summer and fall at the regional transport site (Big Hill) were multiplied by the ratios of [PM10]seasonal mean/[TSP]seasonal mean to account for much of the P being in large particles that do not transport well over the ~25 miles to Lake Tahoe and the likely greater PM exposure at Big Hill compared to forested areas of the western Sierra slope (Cleveland Fire previously burned most of the trees in the area and the site is on an exposed hilltop with some vehicular activity in the vicinity with road access to a microwave tower, heliport, and forest fire lookout).

Mixing Depth – total of 3700 m divided into an upper regional component of 3000 m and a lower local component of 700 m. The mixing depth was not varied by deposition estimate level but was segregated for characterizing the vertical distribution of regional and local pollutants. Essentially all pollutant sources in the Tahoe Basin are near ground level. The rationale for using a 3 km mixing depth for regional pollutants is that vertical air motion during storms and the transport of material over the western slope of the Sierra would entail mixing of the air as it moves up the slopes of the Sierra. Storm clouds lift and mix the air several kilometers above the ridge crest and have an average thickness of about 6000 meters (NWSFO, 2003). Ground-level concentrations of N, P, and PM would be diluted with “cleaner air” aloft. The wet deposition model assumes that the ground-level concentrations are twice the average concentration throughout the 6000-meter mixed layer. In addition, local pollutants were assumed to be uniformly mixed up to 700 meters (the approximate height of Sierra Nevada crest). The model presumes that deeper mixing would allow the locally-generated pollutants to blow out of the Tahoe Basin.

Precipitation Hours – To facilitate the estimation of wet deposition, the seasonal number of precipitation hours was determined by multiplying the number of seasonal days by the seasonal average number of precipitation hours during a day with precipitation. Because the amount and frequency of precipitation can vary dramatically from year to year, this estimate was allowed to vary and to contribute to the range in wet deposition estimates. The number of hours when precipitation occurred during 2003 at Incline

Creek is shown in **Figure 5-6**. The summer precipitation was showery and not likely to be uniform over the Basin on any given day but, on average, the seasonal precipitation frequencies are comparable throughout the basin (**Figure 5-5c**). As shown in **Figure 5-6**, there is a correlation between the number of hours and the amounts of precipitation, with the summer showers being more intense (more water per hour of precipitation). The 2003 precipitation data at Incline Creek and other locations in/near the Tahoe Basin are contrasted in **Figure 5-5**.

Hours of Precipitation per Day – Precipitation during storm passage does not typically occur continuously for 24 hours. During 2003 at Incline Creek, the average number of hours with rain or snow per precipitation day was 6.8, 4.8, 3.7, and 3.0 hours during winter, spring, summer, and fall, respectively. The values used in the bounding analyses ranged from a minimum of 2.7 to a maximum of 7.5 hours per day. The assumption in the wet deposition model is that the each air mass represented by an hour of time (whether in the regional air layer aloft or the local air layer below the Sierra Crest) contains the materials represented by the respective sources (Big Hill for regional) and (mean of SLT-Sandy Way, Thunderbird Lodge, Lake Forest, and DL Bliss SP for local). With each hour, new air masses with similar ambient concentrations enter the Tahoe Basin (i.e., there is no temporal variation in the concentrations of material being advected to the Tahoe Basin and local sources within the Basin rapidly replenish the local material being lost). This assumption will overestimate the actual wet deposition if pollutant concentrations are not rapidly regenerated after wet deposition has occurred. The hourly regeneration assumption is not likely to be valid for the regeneration of primary PM concentrations due to wet surfaces. The lower and upper bound estimates assume a ±10% variation in the number of hours per day of seasonal precipitation. If the variations in the number of days with precipitation and the duration of precipitation are taken together, the lower and upper bound estimates represent a ±38% variation in the number of precipitation hours during any year.

Precipitation Days – The number of days per year with measurable precipitation in the Tahoe Basin was based on 2003 data from Incline Creek, located on the NE side of Lake Tahoe. The number of days with measurable precipitation by season in 2003 was 40, 37, 11, and 4 for winter, spring, summer, and fall respectively. Typically, precipitation during the summer and early fall months is associated with isolated thunderstorms and the precipitation frequencies and amounts on average are roughly similar around the Basin. However, during the passage of synoptic storm systems (generally occurring from November through April), the precipitation amounts on the eastern side of the Lake are about ½ the amount on the western side of the Lake. The frequency of days with precipitation does not vary as much from west to east in the Basin based on the 2003 data; however, analysis of precipitation during additional years is needed to confirm the relatively spatially-uniform frequency. The number of days with precipitation also varies from year to year. Precipitation amounts around the Tahoe Basin during 2003 were generally below normal with an atypical seasonality. Additional analysis is warranted to better quantify the potential variation in wet deposition due to inter-annual variations in the number of precipitation hours. The lower and upper bound estimates assumed a ±25% variation in the number of precipitation days. On an annual basis, this equates to a lower bound of 69 precipitation days, a central estimate of 92 precipitation days, and an upper bound of 115 of precipitation days per year.

Fraction of precipitation to Lake Tahoe – The fraction of the precipitation, cleansing the transported (regional background) pollution that falls directly on Lake Tahoe was assumed to be 5, 10, and 15% respectively for the lower, central, and upper estimates. This parameter for the transported portion of the wet deposition assumes that most of the precipitation and washout of the transported material will occur over the Sierra Nevada due to orographic lifting. As indicated by contours of annual precipitation amounts, only a relatively small portion of the transport washout actually falls directly on Lake Tahoe (**Figure 5-7**). These percentages were applied to the winter and spring seasons when synoptic-scale storms move through the region. During summer and fall when precipitation is more showery, the areal coverage of the scattered showers was assumed to be 5, 10, and 15% respectively for the lower, central, and upper estimates. These are crude estimates based on a thunderstorm being 6-10 km in diameter (Byers, 1965). Compared to the surface area of Lake Tahoe (500 km^2), the area impacted by a thunderstorm (30-80 km^2) represents 6-16% of the Lake's surface. Of course, more than one thunderstorm may develop but they are also more likely to develop over land than the lake itself. Similarly for wet deposition of locally generated pollutants, the fraction of precipitation falling on the Lake was assumed to be 100% during the winter and spring, and to be 5, 10, and 15% respectively for the lower, central, and upper estimates of the areal coverage of scattered showers in summer and fall.

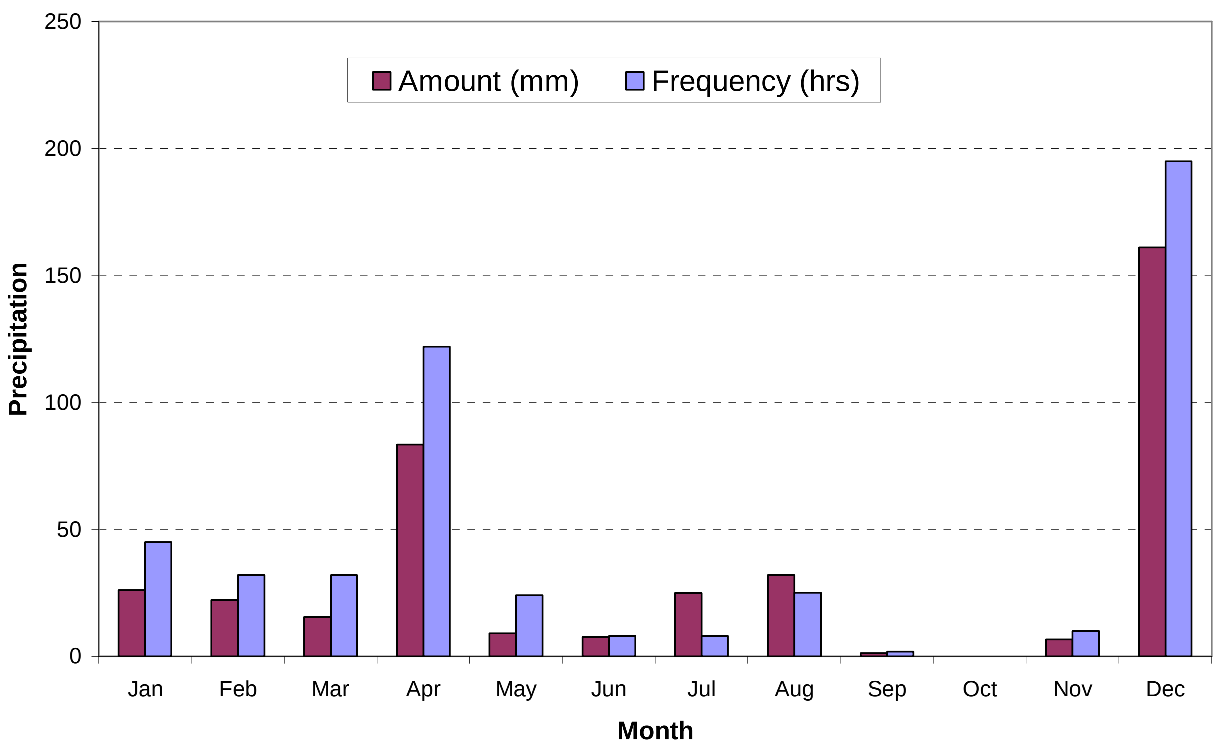
Washout Efficiency – 50, 75, and 100%. Another major assumption in the wet deposition analysis is the efficiency with which the precipitation washes the pollutants out of the atmosphere. This parameter applies a factor to the total mass of material in the volume of air above the Lake to estimate the amount of wet deposition to the lake surface. It quantifies the amount of material actually "washed" out of the air. For this analysis, 50, 75, and 100 percent washout efficiencies were assumed for the bounding estimates. The central estimate is based on Byers (1965) who notes that a modest precipitation rate removes 75% of the aerosols in the column within the first hour of precipitation. Obviously, the upper estimate is the most extreme option possible. The lower bound was set to maintain a comparable deviation from the central estimate.

The detailed results of the CARB wet deposition analysis are presented below and have been divided into "transport" and "local" components to provide a "guestimate" of the relative contributions of regional and local pollution sources to total wet deposition onto Lake Tahoe.

5.3 Estimates of Wet Deposition Associated with Transport

Reiterating, the estimated transport component of the wet deposition to Lake Tahoe assumes that storm systems carry pollutants from the coast and Central Valley of California up the Sierra Nevada slope. Some of the transported pollution, whether initially as condensation nuclei or absorbed on the precipitation, falls directly onto Lake Tahoe. The transport component is based on air quality concentrations measured at the Big Hill site, located about 30 miles upwind of the center of Lake Tahoe and about the same elevation as Lake Tahoe. This site was operated with a comprehensive suite of measurements during LTADS to characterize the regional air pollution (not influenced by local sources) available for potential transport into the Tahoe Basin. No significant anthropogenic emission sources exist between Big Hill and Lake Tahoe. The air quality at Big Hill thus serves as an upper estimate of the concentrations of pollutants actually available for transport to Lake Tahoe because additional dispersion, diffusion, and deposition would occur during any potential air parcel's horizontal and vertical (over the Sierra Nevada) transport to Lake Tahoe. The nitrogenous compounds considered in this deposition assessment were the soluble gases, ammonia (NH_3) and nitric acid (HNO_3), and the soluble ammonium (NH_4^+) and nitrate (NO_3^-) ions found in particles of all sizes (i.e., TSP). Wet deposition estimates are also provided for phosphorus (P) and particulate matter (PM) of all sizes: PM_fine (i.e., PM2.5), PM_coarse (i.e., 2.5 µ < PM_diameter < 10 µ), PM_large (i.e., PM_diameter > 10 µ), which are summed together to represent wet deposition of total PM.

Figure 5-6. Monthly distribution of precipitation at Incline Creek, 2003.



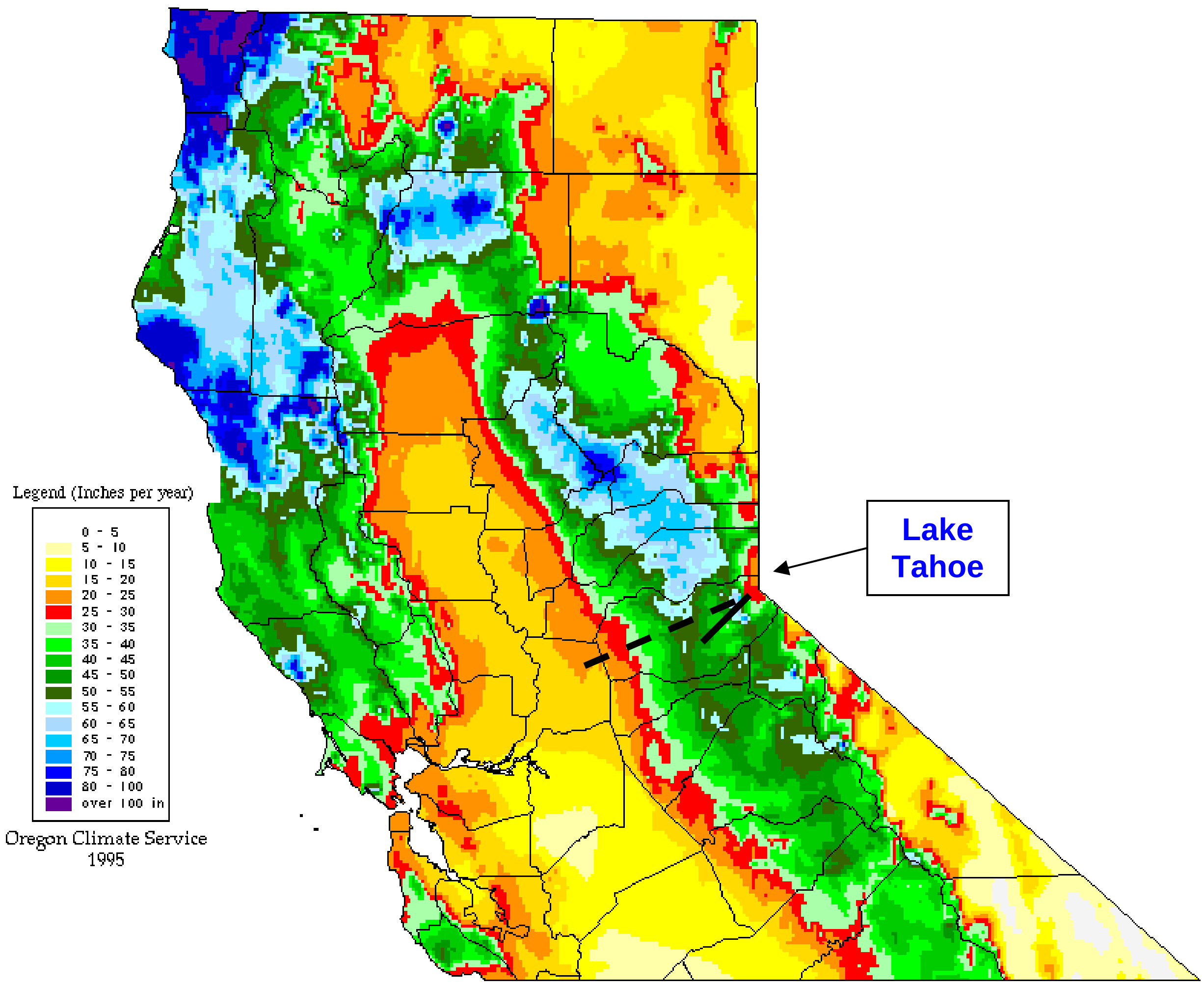
Storms associated with frontal passages (primarily winter and spring) carrying pollutants from the west toward the Tahoe Basin do not drop all of their precipitation directly on Lake Tahoe. Assuming that the air quality at Big Hill is representative of the concentrations along the western slopes of the Sierra Nevada west of Lake Tahoe, an assumption must be made about the proportion of precipitation that occurs along the west-to-east passage of the storms. Because the Sierra Nevada force the air to rise as it crosses them, most of the storm precipitation occurs on the western slopes and crest of the Sierra Nevada, with the Tahoe Basin being somewhat in the rain shadow of the mountain range (**Figure 5-7**). For this analysis, 5, 10, and 15 percent of the total pollutant load in the storm precipitation (along a line from Big Hill to Lake Tahoe) is estimated to fall directly onto Lake Tahoe under the low, central, and upper estimate scenarios. In other words, most of the precipitation and pollutant load falls out before they reach the Tahoe Basin.

Because the pollutant concentrations from the TWS network are 2-week averages and precipitation does not fall constantly for two weeks, the wet deposition analysis matched the minimum 2-week concentrations in the winter and spring seasons with the respective seasonal occurrence (# of hours) of precipitation in the Tahoe Basin (represented by Incline Creek). Because the isolated thunderstorms of summer and fall occur in air with typical seasonal concentrations, seasonal mean pollutant concentrations were used in the wet deposition analysis of the summer and fall seasons. Thus, the transport component of the wet deposition analysis assumes that the concentrations measured at Big Hill are available for potential transport to Lake Tahoe and are represented by the seasonal mean concentrations during summer and fall but by the 2-week minimum seasonal concentrations during winter and spring. These "transportable" concentration estimates (ng/m^3) at Big Hill are shown in **Table 5-3** for TSP_NH_4, TSP_NO_3, P, PM, HNO_3, and NH_3. Considering only the nitrogen component of each compound (shown in parentheses as ng N/m^3), the bulk of the N available for transport is in NH_3, particularly in summer. As might be expected based on emission sources and meteorological processes, the potential for transport of nitrogen, as well as P and PM, to the Tahoe Basin is greatest in the summer and fall when the ground is driest, forest and camping fires are most common, and the long hours of daylight favor more air flow up the western slopes of the Sierra Nevada.

The seasonal transportable concentrations of pollutants in the atmosphere at Big Hill were then multiplied by the seasonal frequency of precipitation events in the Tahoe Basin. Washout of the pollutants was assumed to occur for each hour of precipitation (i.e., new air being advected into Basin had background levels of materials). A cleansing efficiency factor was applied to account for the proportion of material theoretically washed out (i.e., a portion of the pollution load remains in the air). The lower, central, and upper estimates of transported wet deposition assumed 50, 75, and 100 percent vertical washout, respectively, of the pollutant materials in the transport portion of the cylinder of air above Lake Tahoe (i.e., 700 – 3700 m AGL layer).

The direct atmospheric loading of transported (regional background) N, P, and PM to Lake Tahoe was estimated in metric tons as the seasonal representative (N,P,PM) concentrations times the mixing depth (MD, altitude to which material is uniformly mixed and represented by surface concentrations; assumed constant in this analysis but varies diurnally and seasonally) times 5.01×10^{-7} (to convert ng/m^3 to metric tons, assuming surface area of Lake Tahoe = 501 km^2) times the number of precipitation hours (PF) during each season times the horizontal fraction of precipitation downwind of Big Hill that falls directly on Lake Tahoe (HW) times the vertical washout efficiency

Figure 5-7. Annual average precipitation (inches) in Northern California – 1961-90 mean.
(Note the enhanced precipitation along the western slope of the Sierra Nevada due to orographic lifting of the air. Storm systems typically move from the west southwest toward the east northeast. The Tahoe Basin is on the lee side of the Sierra where annual precipitation amounts decline. Integrating along the line from Big Hill upwind air quality site to Lake Tahoe (solid line), the precipitation amount over Lake Tahoe is about 10% of the total precipitation falling along the potential transport route of pollutants from Big Hill to Lake Tahoe. Considering a line from Sacramento (dashed line), the precipitation amount over Lake Tahoe is about 3% of the total precipitation falling along the potential transport route of pollutants from the Central Valley to Tahoe.)



(VW) of the precipitation. In equation form with the subscript "s" representing each season, the seasonal wet deposition due to transport is estimated as:

$$\mathbf{WetDep\_transport_{(N,P,PM)} = ([N,P,PM]_s * MD * PF_s) * 5.01x10^{-7} * HW * VW.}$$

The annual wet deposition is estimated by summing the seasonal values. The lower, central, and upper wet deposition estimates are determined from ranges in values for PF, HW, and VW.

Table 5-3. Concentrations (ng/m^3) observed in each season at Big Hill and used in the LTADS estimation of direct atmospheric wet deposition to Lake Tahoe due to transport (regional background). (Note: Minimum representative 2-week concentrations are shown for winter and spring while seasonal mean concentrations are shown for summer and fall. For P, a base concentration of 40 ng/m^3 was assumed. For the winter and spring seasons when synoptic storms occur, the base concentration was multiplied by the seasonal ratios of the $[TSP]_{2\text{-week minimum}}/[TSP]_{mean}$ at Big Hill. Because most of the P mass is in larger particles (which are not likely to transport the full distance to Tahoe during dry stable conditions), the base [P] was multiplied by the seasonal ratio of [PM10]/[TSP] at Big Hill. Nitrogenous specie concentrations are also shown in parentheses as ng N/m^3.)

[Pollutant] (ng/m^3) **\ Season:**	**Estimate Range**	**winter**	**spring**	**summer**	**fall**
TSP_NH_4	Central	30 (23)	208 (162)	430 (335)	303 (236)
TSP_NO_3	Central	177 (40)	617 (139)	1763 (398)	1394 (315)
HNO_3	Central	87 (19)	99 (22)	1127 (250)	816 (181)
NH_3	Central	65 (53)	89 (73)	984 (810)	719 (592)
TN	Central	(135)	(396)	(1793)	(1324)
P	Central	27	26	30	31
PM	Central	1586	3984	15,165	12,797
PM_fine	Central	563	1905	6887	4962
PM_coarse	Central	344	1795	4855	4898
PM_large	Central	678	284	3423	2938

The estimated transport contributions to the wet atmospheric deposition to Lake Tahoe are presented by pollutant and season in **Table 5-4**. Annually, ammonia is the predominant nitrogen specie being transported and deposited (~8 metric tons N) but ammonium and nitrate particles are slightly lower (~6 metric tons N each). Nitric acid is the least common nitrogen specie being deposited at ~2 metric tons N). Transported phosphorus deposition is less than 2 metric tons per year and PM deposition is a little over 200 metric tons per year. Spring dominates the transported PM deposition with summer a close second, and winter third. The amount of PM deposition transported in fall is small compared to the other seasons. The summer concentrations are greater than in spring but the precipitation frequency is much greater during spring than summer.

Table 5-4. Seasonal estimates of direct atmospheric wet deposition to Lake Tahoe due to transport (regional background) in 2003 (metric tons; N species as N).

Parameter	Estimate \ Season:	winter	spring	summer	fall	Annual
TSP_NH_4	lower bound	0.2	0.7	0.4	0.1	1.3
	central estimate	**0.7**	**3.3**	**1.6**	**0.3**	**5.8**
	upper bound	2.0	8.9	4.3	0.9	16.0
TSP_NO_3	lower bound	0.3	0.6	0.4	0.1	1.4
	central estimate	**1.2**	**2.8**	**1.8**	**0.4**	**6.3**
	upper bound	3.4	7.7	5.1	1.2	17.3
NH_3	lower bound	0.4	0.3	0.8	0.2	1.6
	central estimate	**1.6**	**1.5**	**3.7**	**0.8**	**7.6**
	upper bound	4.5	4.0	10.3	2.2	21.0
HNO_3	lower bound	0.1	0.1	0.3	0.1	0.5
	central estimate	**0.6**	**0.4**	**1.2**	**0.3**	**2.4**
	upper bound	1.6	1.2	3.2	0.7	6.7
Total N	lower bound	0.9	1.8	1.9	0.4	5.0
	central estimate	**4.2**	**7.9**	**8.3**	**1.8**	**22.2**
	upper bound	11.4	21.9	22.8	4.9	61.0
Phosphorus	lower bound	0.0	0.0	0.0	0.0	0.1
	central estimate	**0.1**	**0.1**	**0.0**	**0.0**	**0.3**
	upper bound	0.3	0.3	0.1	0.0	0.7
Particulate Matter	lower bound	2	4	5	1	12
	central estimate	**7**	**17**	**19**	**6**	**48**
	upper bound	18	42	47	14	121
PM_fine	lower bound	0.6	2.0	2.1	0.6	5.3
	central estimate	**2.5**	**7.9**	**8.5**	**2.2**	**21.3**
	upper bound	6.4	19.9	21.4	5.6	53.2
PM_coarse	lower bound	0.4	1.9	1.5	0.6	4.3
	central estimate	**1.6**	**7.5**	**6.0**	**2.2**	**17.3**
	upper bound	3.9	18.7	15.1	5.5	43.2
PM_large	lower bound	0.8	0.3	1.1	0.3	2.5
	central estimate	**3.1**	**1.2**	**4.2**	**1.3**	**9.8**
	upper bound	7.6	3.0	10.6	3.3	24.5

5.4 Estimates of Wet Deposition Associated with Local Pollutant Sources

The calculation of wet deposition due to local sources of nutrients and particulate matter has assumptions similar to those in the transport component. In the case of wet deposition of materials of local origin, it is assumed that precipitation is equally likely to fall on the Lake as on land (where measurements were made) and that the pollutant concentrations are equally high over the Lake as near the shoreline.

The local component assumes that the air pollutants available for removal/washout to the Lake are represented by the seasonal shoreline averages of N, P, and PM concentrations in 4 quadrants (S-SE quadrant represented by South Lake Tahoe-Sandy Way, N-NW quadrant represented by Lake Forest, E-NE quadrant represented by Thunderbird Lodge, and W-SW quadrant represented by Bliss State Park). The lowest representative 2-week pollutant concentrations in winter and spring and seasonal mean concentrations for summer and fall are shown by site and season in **Table 5-1**. The seasonal basin mean concentrations (estimated by the 4-quadrant mean) are shown in **Table 5-5**. Because the number of phosphorus analytical detections was low, the TSP_P concentration for each season was set at 40 ng/m^3. For the local wet deposition estimates, the estimated 40 ng/m^3 [P] at each site was multiplied by the ratios of the seasonal $[TSP]_{2\text{-week minimum}}/[TSP]_{mean}$ during the organized storms of winter and spring. The estimated 40 ng/m^3 P concentration was used directly for the summer and fall calculations (i.e., no depletion in local ambient concentrations when only scattered showers involved).

Given the enhanced wind speeds and vertical air motions during precipitation events and the proximity of local sources to the Lake, TSP was assumed to be transportable to the Lake. The PM_nitrogen species (i.e., NH_4^+ and NO_3^-) being transported to the shoreline were also estimated from the TSP measurements.

The total average N concentrations in the Tahoe Basin were lower than at the upwind Big Hill site during summer and fall when the winds carry pollutants from the Central Valley into the Sierra Nevada. Total N concentrations are comparable at Big Hill and within the Tahoe Basin during the spring when atmospheric mixing is generally good. During the winter however, the Tahoe Total N values are higher than at the Big Hill site due to poorer dispersion of emissions between storms in the Tahoe Basin and weaker advection of pollutants from the Central Valley toward the Sierra Nevada. When storms do transport pollutants, the unstable conditions and wet deposition result in low ambient concentrations at the Big Hill site. At both the upwind site (Big Hill) and the Tahoe sites, NH_3 comprised the bulk of the total N concentrations during summer and fall while particulate NH_4 can also be a significant component in spring.

As was the case for the regional source analysis, the estimate of wet deposition from local sources also assumed a range of meteorological variables, which are listed in **Table 5-2**. Because the number of samples when P was detectable in the Tahoe Basin was low, the analysis assumed a seasonally and spatially constant P concentration. Using an average Tahoe P value of 40 ng/m^3 during LTADS is consistent with ambient measurement techniques, with emission inventory estimates, and with values observed in other sampling programs in the Sierra (dichotomous and toxic measurements).

The range of wet deposition estimates from local sources was created from a range of meteorological estimates. For lower bound, central, and upper bound estimates, many of the meteorological parameter values are naturally the same as those assumed for wet deposition of transported materials. One significant difference in the meteorological assumptions for regional and local sources is the fraction of precipitation washing out directly on the Lake (HW). Because the analysis estimates the amount of pollution in the volume of air directly above the Lake (501 km^2), no fractional correction is needed for the local wet deposition during the winter and spring when widespread storms occur. In the summer and fall when precipitation occurs as scattered rain showers, the areal precipitation fractions used were 5, 10, and 15% for the range of estimates.

The estimated local component of the wet atmospheric deposition to Lake Tahoe is presented by season in **Table 5-6**. As might be expected from the seasonal precipitation distribution, local wet deposition estimates are much higher in winter and spring than during summer and fall. The dominant nitrogen specie in the local deposition component was NH_3. The annual local wet deposition is dominated by the winter and spring seasons.

Table 5-5. Seasonal air quality concentrations (ng/m^3) estimated over Lake Tahoe (i.e., the 4-quadrant mean) and used in the estimation of direct atmospheric wet deposition to Lake Tahoe due to local pollutant sources in 2003. (Note: The 4-quadrant means of the seasonal minimum representative 2-week concentrations are shown for winter and spring while the 4-quadrant mean concentrations are shown for summer and fall. Nitrogenous specie concentrations are also shown in parentheses as ng N/m^3. [P]s in winter and spring are from the baseline [P] (i.e., 40 ng/m^3) multiplied by the seasonal ratios of $[TSP]_{2\text{-week minimum}} / [TSP]_{mean}$.)

[Parameter] (ng/m^3) \ Season:	Estimate Range	winter	spring	summer	fall
TSP_NH_4	fixed	74 (58)	159 (124)	304 (236)	231 (180)
TSP_NO_3	fixed	293 (66)	382 (86)	974 (220)	732 (165)
HNO_3	fixed	280 (62)	177 (39)	599 (133)	675 (150)
NH_3	fixed	251 (207)	197 (162)	625 (515)	654 (539)
TN	fixed	(393)	(412)	(1104)	(1034)
P	fixed	17	29	40	40
PM	fixed	4450	6466	12,413	12,999
PM_fine	fixed	2631	2340	5913	5442
PM_coarse	fixed	1468	3477	5620	5628
PM_large	fixed	351	649	880	1929

Table 5-6. Seasonal estimates* of direct atmospheric wet deposition to Lake Tahoe due to local sources in 2003.

Parameter	Estimate \ Season:	winter	spring	summer	fall	Annual
TSP_NH$_4$	lower bound	1.9	2.6	0.1	0.0	4.5
	central estimate	**4.1**	**5.8**	**0.3**	**0.1**	**10.2**
	upper bound	7.6	10.6	0.7	0.2	19.1
TSP_NO$_3$	lower bound	2.1	1.8	0.1	0.0	4.0
	central estimate	**4.7**	**4.0**	**0.2**	**0.1**	**9.1**
	upper bound	8.7	7.4	0.7	0.1	16.9
NH$_3$	lower bound	6.7	3.4	0.1	0.0	10.2
	central estimate	**14.8**	**7.6**	**0.6**	**0.2**	**23.1**
	upper bound	27.1	13.9	1.5	0.5	43.1
HNO$_3$	lower bound	2.0	0.8	0.0	0.0	2.9
	central estimate	**4.5**	**1.8**	**0.1**	**0.0**	**6.5**
	upper bound	8.2	3.4	0.4	0.1	12.1
Total N	lower bound	12.7	8.7	0.3	0.1	21.7
	central estimate	**28.1**	**19.3**	**1.2**	**0.3**	**48.9**
	upper bound	51.6	35.3	3.3	0.9	91.0
Phosphorus	lower bound	0.1	0.1	0.0	0.0	0.2
	central estimate	**0.2**	**0.3**	**0.0**	**0.0**	**0.5**
	upper bound	0.3	0.5	0.0	0.0	0.8
Particulate Matter	lower bound	23	32	1	0	56
	central estimate	**47**	**63**	**4**	**1**	**115**
	upper bound	78	105	9	3	195
PM_fine	lower bound	13.8	11.4	0.4	0.1	25.8
	central estimate	**27.7**	**22.8**	**1.7**	**0.6**	**52.7**
	upper bound	46.1	37.9	4.3	1.4	89.8
PM_coarse	lower bound	7.7	16.9	0.4	0.1	25.2
	central estimate	**15.4**	**33.8**	**1.6**	**0.6**	**51.5**
	upper bound	25.7	56.4	4.1	1.5	87.7
PM_large	lower bound	1.8	3.2	0.1	0.1	5.1
	central estimate	**3.7**	**6.3**	**0.3**	**0.2**	**10.5**
	upper bound	6.2	10.5	0.6	0.5	17.8

* units are metric tons except that the nitrogen compounds are presented as metric tons of N.

5.5 Summary of Wet Deposition Estimates for 2003

The results of these wet deposition estimates are presented in one seasonal summary by pollutant (**Table 5-7**) and three seasonal summary tables quantifying regional, local, and total wet deposition of total nitrogen, phosphorus, and particulate matter to Lake Tahoe (**Tables 5-8 through 5-10**).

The analysis indicates that the bulk of the N, P, and PM wet deposition originates from local pollution sources (**Figure 5-8**). The bulk of the wet deposition occurs during winter and spring. The greatest transport contribution occurs for PM_NH_4 and PM_NO_3 during the spring and summer. The bulk of the total annual wet deposition occurs during the winter and spring is from local emissions.

The seasonal variations in the relative contribution of each pollutant by source area ought to guide potential emission control decisions to ensure that control efforts will be optimized for effectiveness. It should also be noted for planning purposes that the wet deposition estimates are for 2003 and are based on the precipitation frequency in 2003. Based on the precipitation frequency in 2003 compared to the climatological norm, wet deposition in a normal year would be about 70% of the 2003 estimate that is presented in this report.

Table 5-7. Seasonal estimates of total direct atmospheric wet deposition to Lake Tahoe in 2003 (metric tons*).

Parameter	Estimate \ Season:	winter	spring	summer	fall	annual
TSP_NH_4	lower bound	2.1	3.3	0.5	0.1	5.8
	central estimate	**4.8**	**9.1**	**1.9**	**0.4**	**16.0**
	upper bound	9.6	19.5	5.0	1.1	35.1
TSP_NO_3	lower bound	2.4	2.4	0.5	0.1	5.4
	central estimate	**5.9**	**6.8**	**2.0**	**0.5**	**15.4**
	upper bound	12.1	15.1	5.8	1.3	34.2
NH_3	lower bound	7.1	3.7	0.9	0.2	11.8
	central estimate	**16.4**	**9.1**	**4.3**	**1.0**	**30.7**
	upper bound	31.6	17.9	11.8	2.7	64.1
HNO_3	lower bound	2.1	0.9	0.3	0.1	3.4
	central estimate	**5.1**	**2.2**	**1.3**	**0.3**	**8.9**
	upper bound	9.8	4.6	3.6	0.8	18.8
Total N	lower bound	13.6	10.5	2.2	0.5	26.7
	central estimate	**32.3**	**27.2**	**9.5**	**2.1**	**71.1**
	upper bound	63.1	57.2	26.1	5.8	152.0
Phosphorus	lower bound	0.1	0.1	0.0	0.0	0.3
	central estimate	**0.3**	**0.4**	**0.1**	**0.0**	**0.7**
	upper bound	0.6	0.7	0.1	0.0	1.5
Particulate Matter	lower bound	25	36	6	2	68
	central estimate	**54**	**80**	**22**	**7**	**163**
	upper bound	96	147	56	18	316
PM_fine	lower bound	14.4	13.4	2.5	0.7	31.1
	central estimate	**30.2**	**30.7**	**10.2**	**2.8**	**74.0**
	upper bound	52.4	57.8	25.7	7.0	142.9
PM_coarse	lower bound	8.1	18.8	1.9	0.7	29.5
	central estimate	**17.0**	**41.3**	**7.6**	**2.8**	**68.8**
	upper bound	30.6	75.1	19.2	7.0	130.9
PM_large	lower bound	2.6	3.5	1.2	0.4	7.6
	central estimate	**6.8**	**7.5**	**4.5**	**1.5**	**20.3**
	upper bound	13.8	13.5	11.2	3.8	42.4

* units are metric tons except that the nitrogen compounds are presented as metric tons of N.

Table 5-8. Estimated Wet Deposition of Nitrogen to Lake Tahoe in 2003 (metric tons N).

Estimate	winter	spring	summer	fall	Annual
CARB Lower Bound					
Regional background	0.9	1.8	1.9	0.4	5.0
Local	12.7	8.7	0.3	0.1	21.7
TOTAL	**13.6**	**10.5**	**2.2**	**0.5**	**26.7**
CARB Central Estimate					
Regional background	4.2	7.9	8.3	1.8	22.2
Local	28.1	19.3	1.2	0.3	48.9
TOTAL	**32.3**	**27.2**	**9.5**	**2.1**	**71.1**
CARB Upper Bound					
Regional background	11.4	21.9	22.8	4.9	61.0
Local	51.6	35.3	3.3	0.9	91.0
TOTAL	**63.0**	**57.2**	**26.1**	**5.8**	**152.0**

Table 5-9. Estimated Wet Deposition of Phosphorus to Lake Tahoe in 2003 (metric tons).

Estimate	winter	spring	summer	fall	Annual
CARB Lower Bound					
Regional background	0.0	0.0	0.0	0.0	0.1
Local	0.1	0.1	0.0	0.0	0.2
TOTAL	**0.1**	**0.1**	**0.0**	**0.0**	**0.3**
CARB Central Estimate					
Regional background	0.1	0.1	0.0	0.0	0.3
Local	0.2	0.3	0.0	0.0	0.5
TOTAL	**0.3**	**0.4**	**0.0**	**0.0**	**0.7**
CARB Upper Bound					
Regional background	0.3	0.3	0.1	0.0	0.7
Local	0.3	0.5	0.0	0.0	0.8
TOTAL	**0.6**	**0.8**	**0.1**	**0.0**	**1.5**

Table 5-10. Estimated Wet Deposition of PM to Lake Tahoe in 2003 (metric tons).

Estimate	winter	spring	summer	fall	Annual
CARB Lower Bound					
Regional background	2	4	5	1	12
Local	23	32	1	0	56
TOTAL	**25**	**36**	**6**	**1**	**68**
CARB Central Estimate					
Regional background	7	17	19	6	48
Local	47	63	4	1	115
TOTAL	**54**	**80**	**23**	**7**	**163**
CARB Upper Bound					
Regional background	18	42	47	14	121
Local	78	147	9	3	195
TOTAL	**96**	**189**	**56**	**17**	**316**

Table 5-10a. Estimated Wet Deposition of PM_fine to Lake Tahoe in 2003 (metric tons).

Estimate	winter	spring	summer	fall	Annual
CARB Lower Bound					
Regional background	0.6	2.0	2.1	0.6	5.3
Local	13.8	11.4	0.4	0.1	25.8
TOTAL	**14.4**	**13.4**	**2.5**	**0.7**	**31.1**
CARB Central Estimate					
Regional background	2.5	7.9	8.5	2.2	21.3
Local	27.7	22.8	1.7	0.6	52.7
TOTAL	**30.2**	**30.7**	**10.2**	**2.8**	**74.0**
CARB Upper Bound					
Regional background	6.4	19.9	21.4	5.6	53.2
Local	46.1	37.9	4.3	1.4	89.8
TOTAL	**52.5**	**57.8**	**25.7**	**7.0**	**142.9**

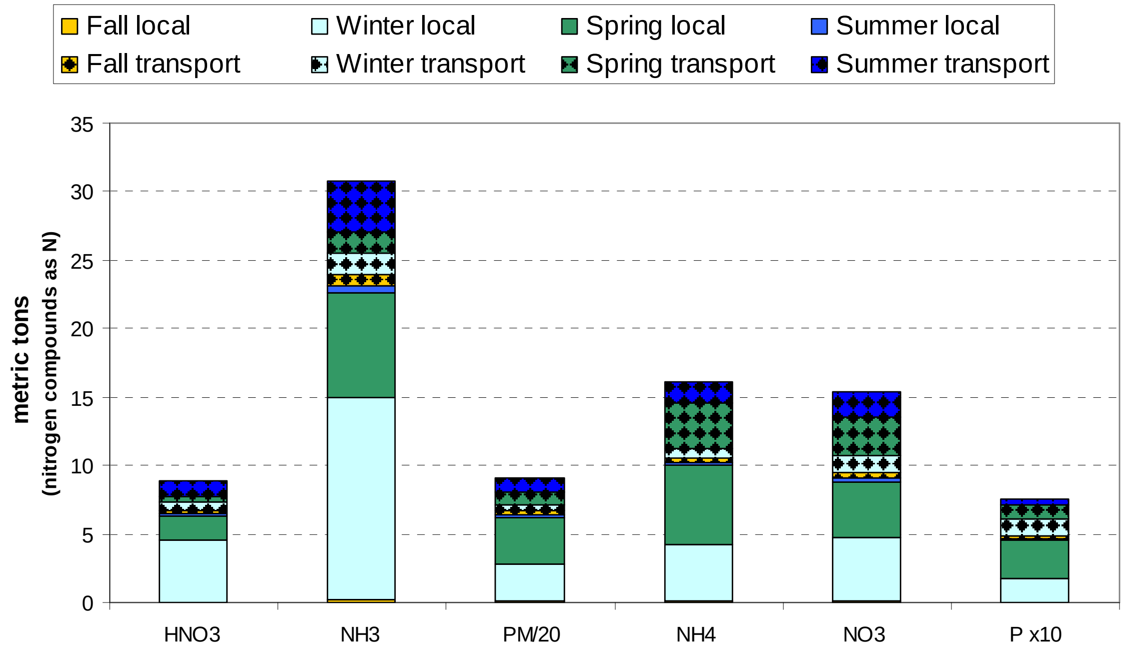
Table 5-10b. Estimated Wet Deposition of PM_coarse to Lake Tahoe in 2003 (metric tons).

Estimate	winter	spring	summer	fall	Annual
CARB Lower Bound					
Regional background	0.4	1.9	1.5	0.6	4.3
Local	7.7	16.9	0.4	0.1	25.2
TOTAL	**8.1**	**18.8**	**1.9**	**0.7**	**29.5**
CARB Central Estimate					
Regional background	1.6	7.5	6.0	2.2	17.3
Local	15.4	33.8	1.6	0.6	51.5
TOTAL	**17.0**	**41.3**	**7.6**	**2.8**	**68.8**
CARB Upper Bound					
Regional background	3.9	18.7	15.1	5.5	43.2
Local	25.7	56.4	4.1	1.5	87.7
TOTAL	**29.6**	**75.1**	**19.2**	**7.0**	**130.9**

Table 5-10c. Estimated Wet Deposition of PM_large to Lake Tahoe in 2003 (metric tons).

Estimate	winter	spring	summer	fall	Annual
CARB Lower Bound					
Regional background	0.8	0.3	1.1	0.3	2.5
Local	1.8	3.2	0.1	0.1	5.1
TOTAL	**2.6**	**3.5**	**1.2**	**0.4**	**7.6**
CARB Central Estimate					
Regional background	3.1	1.2	4.2	1.3	9.8
Local	3.7	6.3	0.3	0.2	10.5
TOTAL	**6.8**	**7.5**	**4.5**	**1.5**	**20.3**
CARB Upper Bound					
Regional background	7.6	3.0	10.6	3.3	24.5
Local	6.2	10.5	0.6	0.5	17.8
TOTAL	**13.8**	**13.5**	**11.2**	**3.8**	**42.4**

Figure 5-8. Seasonal estimates of wet deposition to Lake Tahoe during 2003 due to local and regional sources.



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.

5.6 Comparison with Measurements from Surrogate Surfaces

The Tahoe Research Group (TRG) has collected deposition data for a number of years with a variety of surrogate surface samplers at a limited number of locations. These deposition samplers are briefly described in Appendix A. Only the Wallis Residence (tower) site in Tahoe City (aka Ward Lake Level) has a long-term data record for deposition. CARB staff has reservations about the representativeness of this sampling site because trees have grown around the sampling tower (**Figure 5-9**). In particular, deciduous trees have grown immediately adjacent to the tower, have been cut back, and have re-grown to a height exceeding that of the deposition samplers. These trees likely have an irregular impact on deposition at this site as the impact likely depends on wind direction, wind speed, and season (e.g., leaves, pollen, insects, birds). Wet deposition estimates from surrogate surfaces presumably would have fewer variables affecting the deposition amounts than the dry deposition estimates because the falling precipitation would not be as impacted by sampler- or tree-induced turbulence. The TRG dry deposition bucket sampler was modified in 1989 to include distilled de-ionized water to better represent dry deposition to a water surface. This modification was a particularly significant improvement in N deposition estimates to Lake Tahoe because the measurements then included the contribution of water-soluble gases such as ammonia and nitric acid.

These surrogate surface deposition samplers also receive particulate matter of all sizes (e.g., dust, detritus, pollen, insects, bird droppings) in contrast to the LTADS samplers

(TWS and MVS) which did not collect particles greater than 25 – 30 µm in aerodynamic diameter. As an anecdotal illustration, pine pollen in the spring and early summer is known to cover surfaces and to cover Lake Tahoe and is also captured in the surrogate surface samplers; it is noteworthy that the deposition samples with operator notes indicating the presence of pollen in the sample also tended to have higher phosphorus and ammonium loadings than other samples. Removal of these “pollen-contaminated” samples helped to create the large difference between the “raw” and “edited” wet deposition results shown for the Ward Lake Level site in **Table 5-11**. In late 2001, a National Acid Deposition Program (NADP) site (Sagehen Creek) was established northwest of the Tahoe Basin. Measurements for this site in the NDAP program are also included in **Table 5-11** to provide an additional context of the wet deposition data collected in the Sierra Nevada near Lake Tahoe. Of additional interest is the apparent potentially large year-to-year variation in wet deposition exhibited at the Sagehen site.

The CARB annual wet deposition estimates (i.e., 31 metric tons as N of NH_4^+ and NO_3^-, 71 metric tons of TN, and 1 metric ton of P) are about 30% lower for total nitrogen and 20% lower for nitrogen (ammonium plus nitrates) but about 75% lower for total phosphorus than with the edited data from the surrogate surface (bucket) method (**Table 5-11**). The lower LTADS estimates are not unexpected because the Ward LL site is more heavily impacted than other deposition sampling sites near and on Lake Tahoe. A wet deposition comparison for PM cannot be made because no PM measurements are being made with the current surrogate sampler methods.

Another factor in the comparison of P wet deposition estimates by CARB and TRG is that the CARB P assumes total P. However, the wet/dry deposition bucket measurements have indicated that approximately 50% of the total P is biologically active and available. Thus, CARB’s Central Estimate of P wet deposition to Lake Tahoe from the atmosphere likely overestimates the amount of biologically available P being deposited to the Lake from the atmosphere by up to a factor of two.

A seasonal comparison of the LTADS wet deposition estimates with the TRG measurements during 2003 (and with the National Acid Deposition Monitoring Program measurements during 2003 and 2004 of HN_4^+ and NO_3^- at Sagehen northwest of the Tahoe Basin) is provided in **Figures 5-10a-d**. The central LTADS estimate is indicated by the circle with the upper and lower extremes (representing minimum and maximum conceivable estimates, very low probability of being beyond the bounds). The TRG measurement results indicate the range of the original (raw) measurements and the results after editing suspect samples. Except for NO_3^-, the LTADS wet deposition estimates for 2003 are in rough agreement with the TRG measurements. Most of the LTADS estimates are lower than the TRG measurements, especially during summer and fall. The primary reason for this is likely that the LTADS estimate is based on the frequency of precipitation while the TRG measurements are pro-rated to the total amounts of precipitation. Thus, the TRG measurement procedure may be biased high if pollutant washout occurs primarily during the beginning of storms and deposition is not constant throughout the precipitation event. Also of interest is the magnitude of the inter-annual variation in deposition results for Sagehen.

Table 5-11. Wet Deposition Rate Measurements Extrapolated to Lake Tahoe (metric tons/year; nitrogen data are in metric tons N per year).
(Note: Measurements of PM deposition are not made with the surrogate surface samplers used by TRG or NADP. The NADP analysis does not include TKN or P.)

Estimate	Nitrogen+	Phosphorus	PM
TRG Wet			
3-site (WY82)[1]	36.3	2.3	---
3-site (5/83-6/84)[2]	44.2	2.4	---
Ward LL (1989-91)[3]	29.0	5.0	---
Ward LL (1989-91)[4]	40.2	5.1	---
Ward LL raw / edited (2003)	70.2 / 52.3	4.6 / 3.8	---
Ward LL raw / edited (2003)*	103.9* / 109.8*		---
NADP Wet		---	
Sagehen Creek (2003)	38.2	---	---
Sagehen Creek (2004)	16.2	---	---

+ – Nitrogen measurement only includes NH_4^+ and NO_3^- except when marked with an asterisk
* – Nitrogen includes total kinetic nitrogen (TKN, primarily NH_3), in addition to NH_4^+ and NO_3^-
[1] – sites: Incline Village, Glenbrook, & Meyers
[2] – sites: Tahoe Vista & SLT-Bijou
[3] – Jassby (1994); assuming 90 days with precipitation
[4] – Reuter and Tarney (2004)

Figure 5-9. TRG Ward Lake Level (aka Wallis Tower) deposition sampling site.

5.7 Wet and Dry Deposition

The estimates of wet deposition summarized in Section 5.5 derive from an analysis based upon basic principles and a wide range of assumptions. The estimates of dry deposition provided in Chapter 4 were based upon established modeling methods but also required some assumptions to deal with uncertainty in variables that were not quantified through observations. Because the dry deposition estimates are derived through established modeling methods and required fewer assumptions, they are expected to be more reliable than the estimates of wet deposition. Recall too from previous chapters the various assumptions that would affect the deposition estimates. For example, the PM deposition estimates assume that all particles are insoluble. In reality, the TWS sampling results indicate that 20-25% of the particle mass is soluble. Thus, the actual PM deposition affecting water clarity is about 75-80% of the amounts reported in this chapter. Also, as noted in Chapter 2, the wet deposition estimates for a year with a “normal” precipitation frequency could be decreased from the 2003 estimate by, at most, another 30% for both particulate and gaseous pollutants.

Bearing in mind that a lower level of confidence is associated with the estimates of wet deposition compared to those for dry, the two are nonetheless combined in the tables that follow in this section for the convenience of those persons primarily interested in obtaining estimates of the approximate total atmospheric deposition to the Lake. Note too that these atmospheric deposition estimates are for 2003. Central, lower, and upper bound estimates of wet and dry deposition are combined in **Tables 5-12, 5-13, and 5-14** to provide central, lower, and upper bound estimates of total atmospheric deposition. It is also important to remember the different caveats and uncertainties associated with the total deposition estimates by LTADS and total deposition measurements by TRG. As shown in **Figures 5-11a) and b)**, significant differences exist between the two approaches for ammonium (TRG ~2x LTADS) and nitrates (TRG ~3x LTADS). Because the TRG dry deposition method is water-based, ammonia and nitric acid, both of which are water soluble, may be included in the ammonium and nitrates measurements. This possibility is reinforced by the fact that the two methods are in approximate agreement for the estimates of Total Nitrogen (**Figure 5-11c)**). The total phosphorus deposition estimates by LTADS are 50-70% lower than the TRG estimates, which is not unreasonable given the biases in the two methods (**Figure 5-11d)**). As indicated by the range between the bounding estimates, the uncertainty of the LTADS central estimate cannot be considered to be less than ±50%.

Figure 5-10a. Seasonal comparison of LTADS estimate with TRG measurement of ammonium (NH_4^+) wet deposition at Lake Tahoe during 2003.

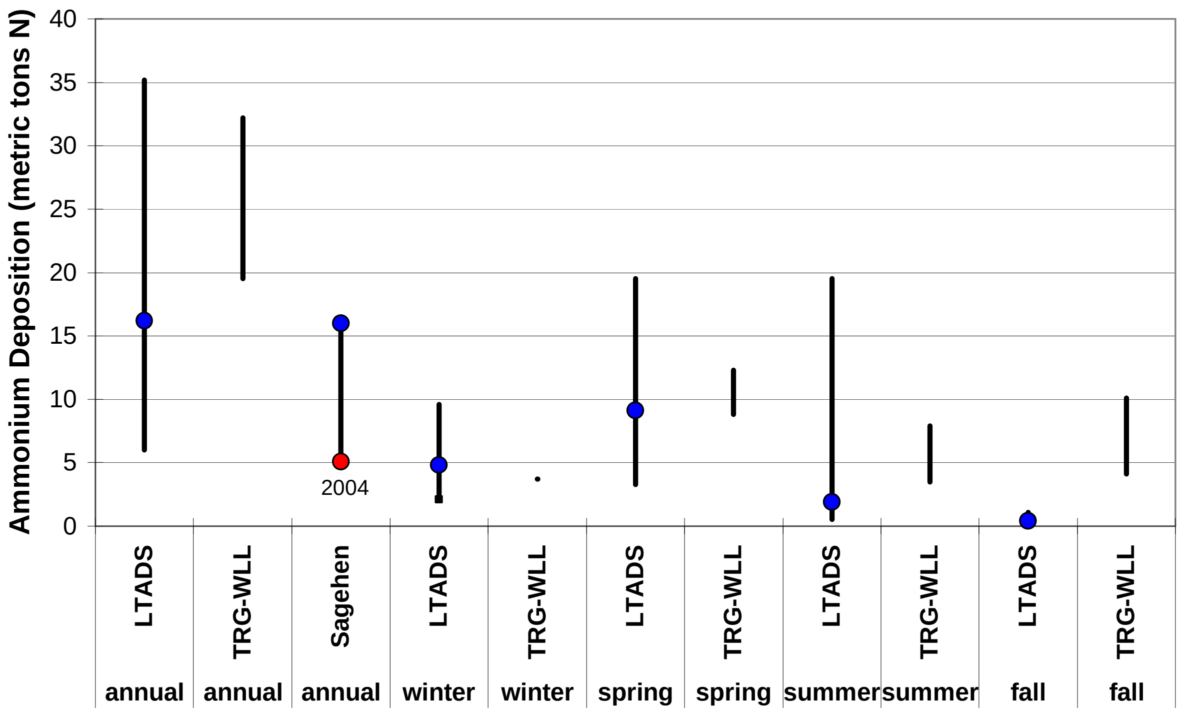


Figure 5-10b. Seasonal comparison of LTADS estimate with TRG measurement of nitrate (NO_3^-) wet deposition at Lake Tahoe during 2003.

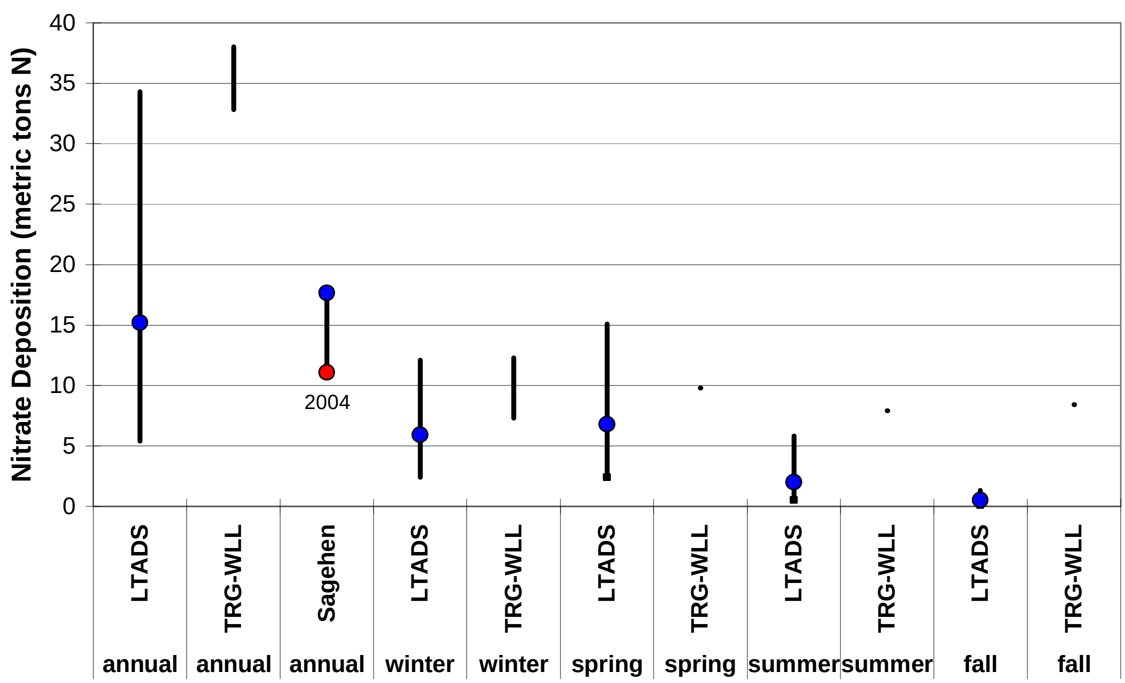


Figure 5-10c. Seasonal comparison of LTADS estimate with TRG measurement of total nitrogen wet deposition at Lake Tahoe during 2003. LTADS data include NH_4^+, NO_3^-, NH_3, and HNO_3 while TRG data include NH_4^+, NO_3^-, and TKN.

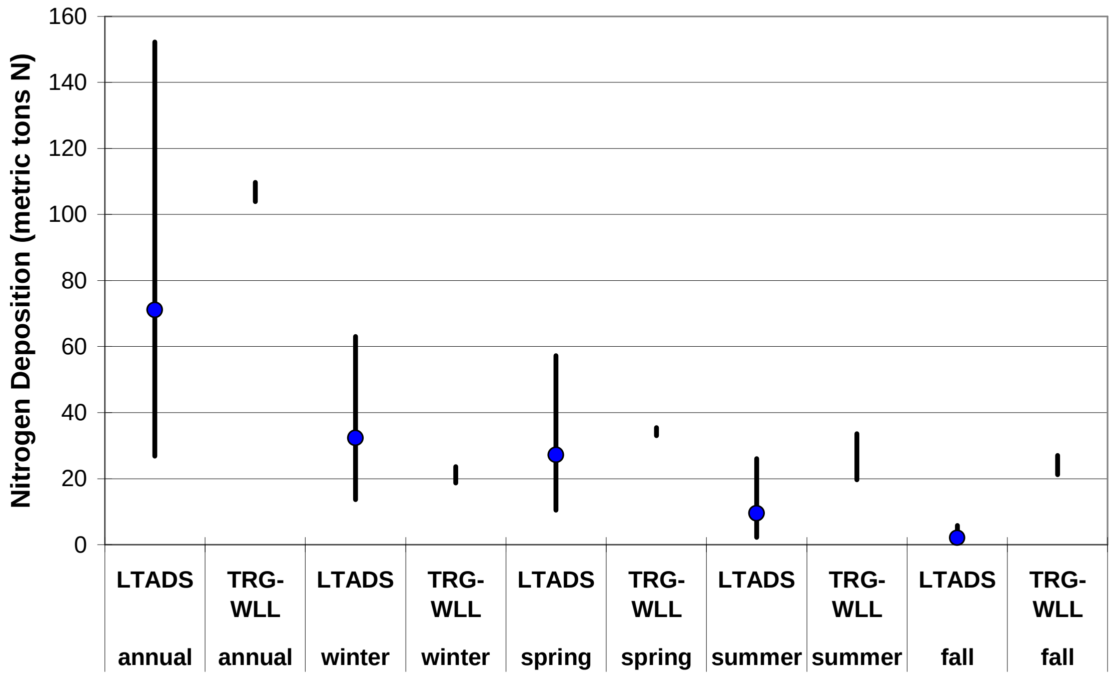


Figure 5-10d. Seasonal comparison of LTADS estimate with TRG measurement of total phosphorus wet deposition at Lake Tahoe during 2003.

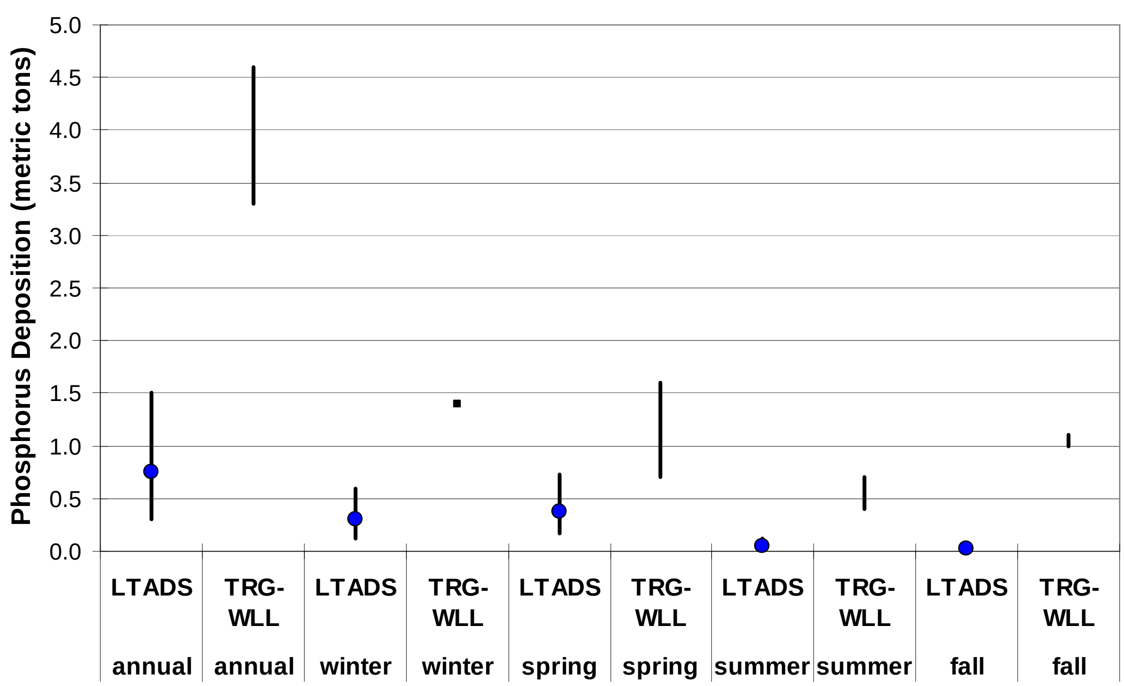


Table 5-12. Central estimates of dry and wet deposition to Lake Tahoe in 2003 combined to provide a central estimate of total deposition (metric tons; nitrogenous compounds as metric tons N).

Parameter	Estimate \ Season:	winter	spring	summer	fall	Annual
TSP_NH4	Central dry	1.1	3.0	3.2	2.5	10
	Central wet	4.8	9.1	1.9	0.4	16
	Total	**5.9**	**12.1**	**5.1**	**2.9**	**26**
TSP_NO3	Central dry	1.0	2.0	3.0	2.1	8
	Central wet	5.9	6.8	2.0	0.5	15
	Total	**6.9**	**8.8**	**5.0**	**2.6**	**23**
NH3	Central dry	17.7	12.8	19.4	26.4	76
	Central wet	16.4	9.1	4.3	1.0	31
	Total	**34.1**	**21.9**	**23.7**	**27.4**	**107**
HNO3	Central dry	5.8	3.3	5.0	7.4	22
	Central wet	5.1	2.2	1.3	0.3	9
	Total	**10.9**	**5.5**	**6.3**	**7.7**	**31**
Total N	Central dry	25.6	21.1	30.6	38.4	116
	Central wet	32.3	27.2	9.5	2.1	71
	Total	**57.9**	**48.3**	**40.1**	**40.5**	**187**
Phosphorus	Central dry	0.6	0.6	0.6	0.6	2.2
	Central wet	0.3	0.4	0.0	0.0	0.7
	Total	**0.9**	**1.0**	**0.6**	**0.6**	**2.9**
Particulate Matter	Central dry	153	131	167	135	590
	Central wet	54	80	23	7	163
	Total	**207**	**211**	**190**	**142**	**753**

Table 5-13. Lower bound estimates of dry and wet deposition to Lake Tahoe in 2003 combined to provide a lower bound estimate of total deposition (metric tons; nitrogenous compounds as metric tons N).

Parameter	Estimate \ Season:	winter	spring	summer	fall	Annual
TSP_NH4	low dry	0.7	1.8	1.8	1.5	6
	low wet	2.1	3.3	0.5	0.1	6
	Total	**2.8**	**5.1**	**2.3**	**1.6**	**12**
TSP_NO3	low dry	0.6	1.2	1.7	1.2	5
	low wet	2.4	2.4	0.5	0.1	5
	Total	**3.0**	**3.6**	**2.2**	**1.3**	**10**
NH3	low dry	11.5	8.7	12.6	17.3	50
	low wet	7.1	3.7	0.9	0.2	12
	Total	**18.6**	**12.4**	**13.5**	**17.5**	**62**
HNO3	low dry	3.7	2.2	3.3	4.8	14
	low wet	2.1	0.9	0.3	0.1	3
	Total	**4.3**	**4.2**	**5.1**	**3.8**	**17**
Total N	low dry	16.5	13.8	19.4	24.8	74
	low wet	13.6	10.5	2.2	0.5	27
	Total	**30.1**	**24.3**	**21.6**	**25.3**	**101**
Phosphorus	low dry	0.2	0.2	0.1	0.2	0.7
	low wet	0.1	0.1	0.0	0.0	0.3
	Total	**0.3**	**0.3**	**0.1**	**0.2**	**1.0**
Particulate Matter (TSP)	low dry	95	80	98	84	360
	low wet	25	36	6	1	68
	Total	**120**	**116**	**104**	**85**	**428**

Table 5-14. Upper bound estimates of dry and wet deposition to Lake Tahoe in 2003 combined to provide an upper bound estimate of total deposition (metric tons; nitrogenous compounds as metric tons N).

Parameter	Estimate \ Season:	winter	spring	summer	fall	Annual
TSP_NH4	high dry	1.7	4.6	4.9	3.8	15
	high wet	9.6	19.5	5.0	1.1	35
	Total	**11.3**	**24.1**	**9.9**	**4.9**	**50**
TSP_NO3	high dry	1.5	3.0	4.6	3.2	12
	high wet	12.1	15.1	5.8	1.3	34
	Total	**13.6**	**18.1**	**10.4**	**4.5**	**46**
NH3	high dry	26.0	18.1	28.2	38.4	110
	high wet	31.6	17.9	11.8	2.7	64
	Total	**57.6**	**36.0**	**40.0**	**41.1**	**174**
HNO3	high dry	8.5	4.7	7.3	11.0	31
	high wet	9.8	4.6	3.6	0.8	19
	Total	**18.3**	**9.3**	**10.9**	**11.8**	**50**
Total N	high dry	37.7	30.3	45.0	56.3	170
	high wet	63.1	57.2	26.1	5.8	152
	Total	**100.8**	**87.5**	**71.1**	**62.1**	**322**
Phosphorus	high dry	0.7	0.8	0.8	0.8	3.2
	high wet	0.6	0.8	0.1	0.0	1.5
	Total	**1.3**	**1.6**	**0.9**	**0.8**	**4.7**
Particulate Matter	high dry	224	191	250	196	900
	high wet	96	147	56	17	316
	Total	**320**	**338**	**306**	**213**	**1216**

Figure 5-11a. Total (wet + dry) ammonium (NH_4^+) deposition estimates for 2003.

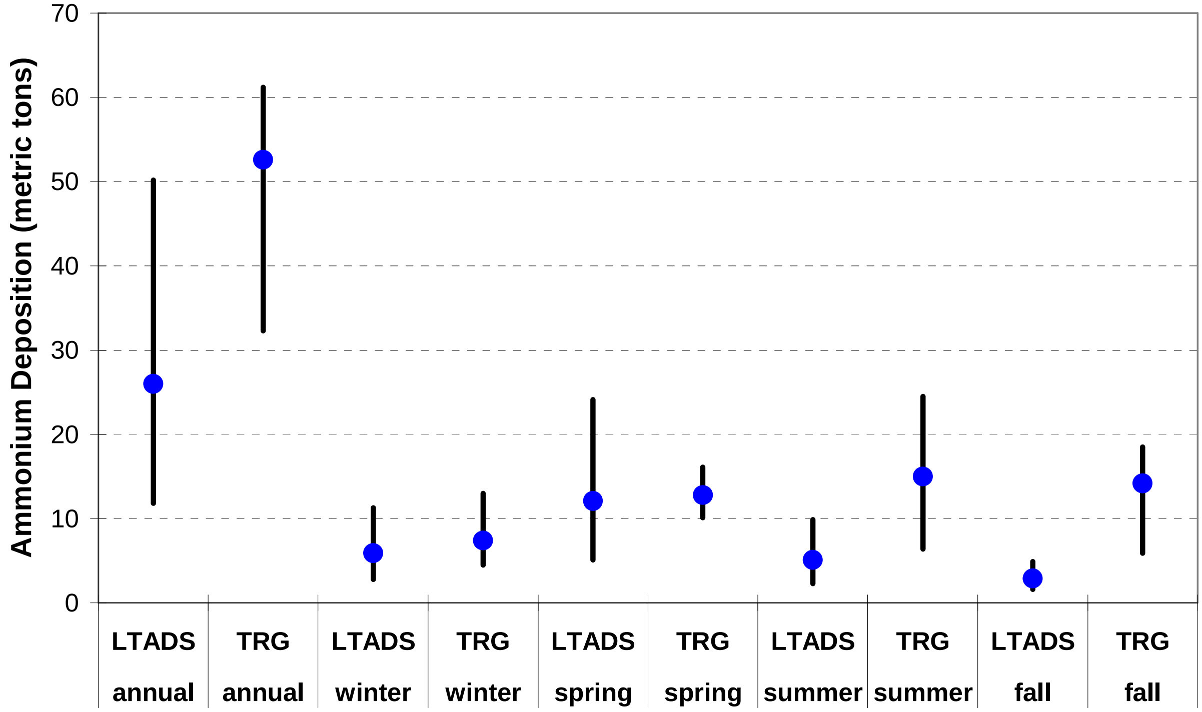


Figure 5-11b. Total (wet + dry) nitrates (NO_3^-) deposition estimates for 2003.

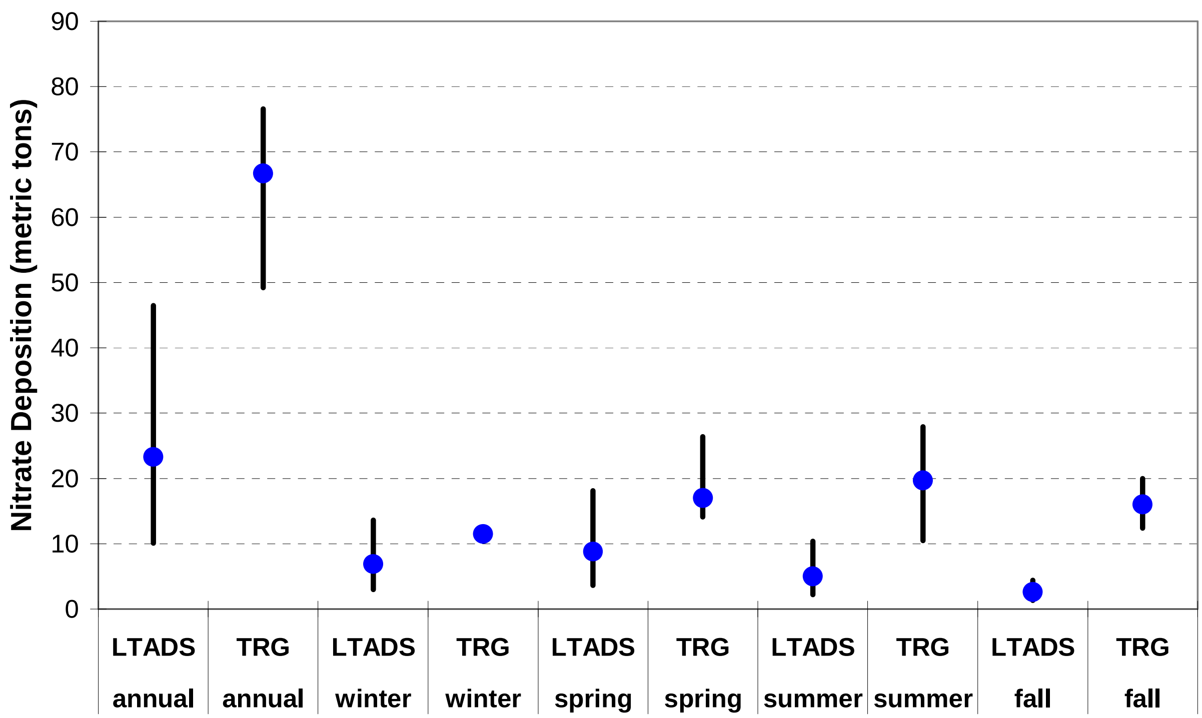


Figure 5-11c. Total (wet + dry) total nitrogen (TN) deposition estimates for 2003.

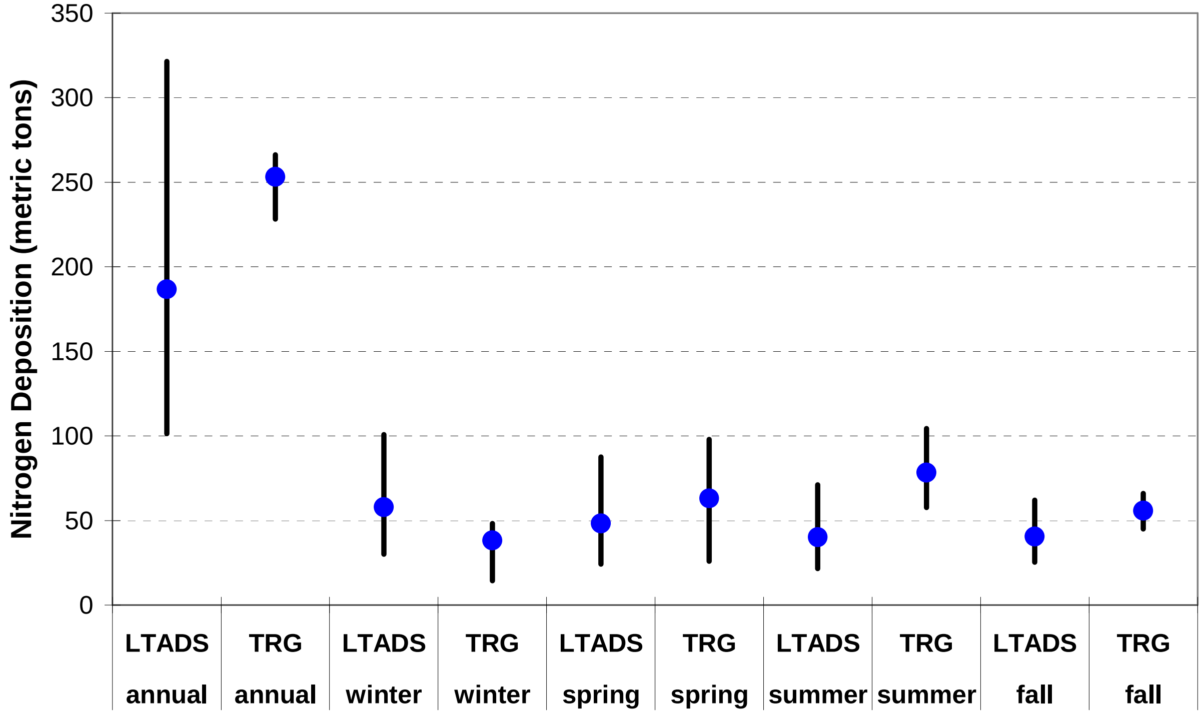
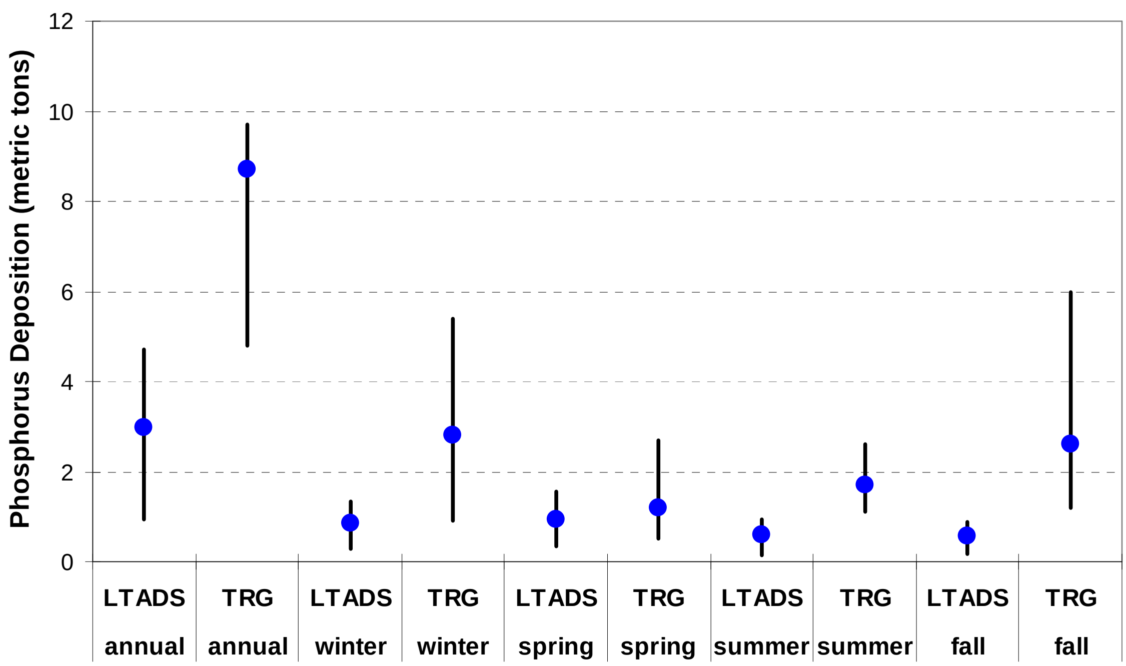


Figure 5-11d. Total (wet + dry) phosphorus (P) deposition estimates for 2003.



5.8 References

Byers, H.R. (1965). In *Elements of Cloud Physics*, University of Chicago Press, Chicago, p. 28.

Hales, J.M. (1991). "Atmospheric process research and process model development", in *Acidic Deposition: State of Science and Technology, Vol. I: Emissions, Atmospheric Processes, and Deposition*. U.S. National Acid Precipitation Program, Washington, DC.

Hales, J.M. (1995). "Acidic Precipitation", Ch. 12 in H.B. Singh, ed., *Composition, Chemistry, and Climate of the Atmosphere*, Van Nostrand Reinhold, New York, pp. 443-479.

Jassby, A. D., Reuter, J. E., Axler, R. P., Goldman, C. R., and S. H. Hackley (1994). "Atmospheric deposition of nitrogen and phosphorus in the annual nutrient load of Lake Tahoe", *Water Resources Research*, **30**, 7, 2207-2216, July.

National Weather Service Forecast Office (2003). "WFO Sacramento County Warning Area Meteorology" (http://www.wrh.noaa.gov/sto/CWA.php).

Reuter, J.E. and L.W. Tarnay. (2004). "Analytical review of nutrient deposition to Lake Tahoe. I. Nitrogen." Tahoe Research Group, John Muir Institute for the Environment, University of California, Davis. 13 p.

Schumann, T., Zinder, B., Waldvogel, A. (1988). "Aerosol and hydrometeor concentrations and their chemical composition during winter precipitation along a mountain slope -- I. Temporal evolution of the aerosol, microphysical and meteorological conditions." *Atmospheric Environment* **22**(7), pp. 1443-1459.

Zinder B., Schumann T., and Waldvogel A. (1988) "Aerosol and hydrometer concentrations and their chemical composition during winter precipitation along a mountain slope -- II. Enhancement of below-cloud scavenging in a stably stratified atmosphere." *Atmospheric Environment* **22**(12), pp. 2741-2750.

This page blank intentionally.