Utah Lake Water Quality Study Atmospheric Deposition Decision Support Document

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Executive Summary

As part of the nutrient criteria development process for Utah Lake, mass balances of the nitrogen (N) and phosphorus (P) sources will be developed to inform the construction and calibration of in-lake water quality models. Nutrient inputs to the lake include surface water, groundwater, and atmospheric deposition. As part of the effort to resolve the mass balance of N and P in Utah Lake, the Science Panel must recommend atmospheric N and P loading values. To reach this goal, the Science Panel formed a Subgroup to review, analyze, and synthesize information and data from previous studies on atmospheric deposition. This effort was a continuation and culmination of work conducted by Science Panel members and external researchers since 2018. The Subgroup achieved the following objectives: (1) analyze available information and data to improve understanding of atmospheric deposition to Utah Lake, (2) work collaboratively toward a recommendation for atmospheric loading, and (3) document the Science Panel's decision-making process for analyzing and evaluating evidence and working toward an atmospheric deposition recommendation.

Data from atmospheric deposition samplers was obtained from two separate studies led by Dr. Gus Williams and Dr. Wood Miller. Samples were collected for total phosphorus (TP), dissolved inorganic nitrogen (DIN), and individual constituents comprising soluble reactive phosphorus (SRP), nitrate, and ammonium. The raw sampler data were reviewed and summarized; outliers evaluated for potential contamination, weather events, and local deposition sources; and flux estimates imputed for missing sampling dates. Several decisions were made regarding the processing of individual samples, including the following:

- Sample concentrations were converted to area-based fluxes for the W. Miller dataset by pairing samples with precipitation data from the nearest precipitation gage.
- Insects were acknowledged as a potential source or sink of nutrients to Utah Lake but were considered separately from atmospheric deposition. Therefore, samples containing insects were considered contaminated and were removed from consideration.*
- Missing sampling events were imputed using a regression model using local weather data. Data from the Williams dataset were prioritized for estimating lakewide atmospheric deposition due to uncertainties arising from the sampling approach employed for the W. Miller dataset.

Cumulative annual N and P fluxes were computed for each sampling site by summing each individual sampling event throughout the year. To determine how these shoreline sampling sites translate across the lake, the potential for attenuation of fluxes moving away from the shoreline was evaluated. Data from a sampler placed on Bird Island was analyzed, and analyses showed higher N and P fluxes at Bird Island than at shoreline samplers. The expectation was that fluxes at Bird Island would be less than or equal to fluxes on the shoreline, so additional hypotheses were evaluated. The first was a potential that shoreline fluxes at a non-sampled area around the lake contributed to higher fluxes at Bird Island. This hypothesis was evaluated using wind rose

* The Subgroup did not achieve consensus on this decision. In the absence of consensus, the Subgroup made this decision by majority. The majority and minority perspectives are documented in this report.

data, but the potential source of additional nutrient deposition was not definitively identified. The second hypothesis was that Bird Island collects nutrients from an in-lake source such as bird droppings, volatilized nutrients from the island, or lake water spray. Quality assurance testing and field metadata could not definitively rule out this hypothesis. The Subgroup determined that in the absence of explaining the higher fluxes observed at Bird Island, this sampler would not be used to evaluate attenuation of fluxes across the lake.* Rather, information from the atmospheric deposition literature were used to quantify the potential attenuation rates of locally-sourced atmospheric deposition. Potential attenuation distances of 100-2,000 m were identified.*

It was anticipated that regional sources of atmospheric deposition would be expected across all of Utah Lake, and the only atmospheric deposition sources that would be expected to attenuate would be local sources. The shoreline samplers collect both local and regional deposition, and it was not possible to parse the relative amounts of these sources. Instead, literature from the Utah Lake basin were used to quantify regional deposition. The assumption was that (a) areas near the shoreline of the lake receive both local and regional sources of atmospheric deposition, and (b) areas near the center of the lake receive only regional sources of atmospheric deposition. Atmospheric deposition loads to Utah Lake were calculated by:

1. Estimating shoreline fluxes between samplers using a spatial interpolation technique called inverse distance weighted interpolation
2. Assigning proportional contributions of shoreline samplers (local + regional flux) and regional flux estimates, with proportions for shoreline samplers highest near the shoreline and proportions for regional flux highest away from the shoreline.
3. Calculating the total N and P flux across the lake by summing flux rates across the raster layer of fluxes in the lake
4. An additional scenario was run assuming no attenuation, using inverse distance weighted interpolation to spatially interpolate shoreline sampling sites across the lake.

The majority of Subgroup members recommended that atmospheric deposition loading to Utah Lake be considered as 32 metric tons/yr TP and 220 metric tons/yr DIN, with a potential range of 31-45 metric tons/yr TP and 218-249 metric tons/yr DIN that could be evaluated as part of a model sensitivity analysis.* These ranges reflected different attenuation distances. The Subgroup concluded this was the best available estimate of atmospheric deposition to Utah Lake based on current evidence, and ongoing research will continue to advance the collective understanding of atmospheric deposition to Utah Lake. The chemical speciation of TP and DIN was calculated from direct measurements in the Williams dataset, representing an average of 37.5% of TP as SRP, 20.25% of DIN as nitrate, and 69.75% of DIN as ammonium. These measured constituents did not match completely with the input data needed to characterize the Utah Lake Nutrient Model (including organic N and P), but the specifics on implementing the observed proportions were recommended to be determined by the modeling team.

* The Subgroup did not achieve consensus on these decisions. In the absence of consensus, the Subgroup made these decisions by majority. The majority and minority perspectives are documented in this report.

One Subgroup member did not support the Subgroup's recommendation and was invited to provide a memo with their diverging perspectives. The memo and reference material are included in the appendix of this report.

Background

Characterizing the mass balance of nitrogen (N) and phosphorus (P) entering and exiting Utah Lake is fundamental to the Science Panel's understanding of nutrient cycling within the lake. It is also essential for the Science Panel to develop responses to the Steering Committee's Charge Questions, construct and calibrate in-lake water quality models, and develop N and P water quality criteria. Nutrient inputs to Utah Lake are comprised of groundwater inflow, tributary and overland inflows, precipitation, and atmospheric deposition. A recent analysis commissioned by the Science Panel (Tetra Tech, 2021) computed a mass balance for the groundwater and tributary sources.

Studies to characterize wet and dry atmospheric deposition of nutrients to Utah Lake were initiated by the Wasatch Front Water Quality Council (WFWQC) and Brigham Young University in 2018, with initial results presented to the Science Panel in spring of 2019. Throughout 2019 and the first half of 2020 the Science Panel worked with the WFWQC, primarily through discussions with Science Panel member Dr. Theron Miller, to guide ongoing and future atmospheric deposition monitoring. That effort resulted in several products including: 1) a preliminary atmospheric deposition load estimate; 2) a revised atmospheric deposition monitoring plan; and 3) a set of overarching recommendations from the Science Panel to the WFWQC to guide the atmospheric deposition monitoring program. A chronological accounting of these discussions and resulting products was provided to the Steering Committee on May 28, 2020 (ULWQS Science Panel, 2020).

In 2022, the Science Panel revisited their atmospheric recommendation with new data presented by WFWQC. On March 3, 2022, Dr. Theron Miller, Dr. Wood Miller, and Dr. Gus Williams presented the results from their studies to the Science Panel. Over several meetings, Science Panel members reviewed atmospheric deposition studies and attempted to generate a single atmospheric deposition value for P and N to recommend to the ULWQS modeling to calibrate the Utah Lake in-lake water quality model. At the August 3 Science Panel meeting, Science Panel members decided to form a subgroup that would regularly meet to discuss assumptions, aggregate and analyze available atmospheric deposition data, and recommend an atmospheric deposition N and P loading value for Utah Lake.

The ULWQS Atmospheric Deposition Subgroup members included Dr. Mike Brett, Dr. Mitch Hogsett, Dr. Theron Miller, and Dr. Hans Paerl. The Subgroup met from August 18 to February 2. In total, Subgroup members attended 19 meetings to review, discuss, and analyze atmospheric deposition data. This report documents the results of their discussion and their recommendations for calculating an atmospheric deposition loading value to Utah Lake. This report also documents when Subgroup members were able to reach consensus on analysis decisions and when there were diverging perspectives within the Subgroup and why.

Analysis Plan Development

The Subgroup developed an analysis plan to achieve the following objectives:

1. Analyze available information and data to improve understanding of atmospheric deposition to Utah Lake
2. Work collaboratively toward a recommendation for atmospheric loading, ideally achieved through consensus
3. Document the SP's decision-making process for analyzing and evaluating evidence and working toward an atmospheric deposition recommendation

The purpose of the analysis plan was to agree on the process by which atmospheric loading recommendations would be generated, prior to generating results. The detailed analysis plan is included in the Appendix. To summarize, the analysis plan included the following steps:

- Review and summarize data from atmospheric deposition samplers around Utah Lake
- Evaluate outlier samples for potential explanations such as collection methodology, contamination, weather events, and local sources
- Review and discuss previous Science Panel and third-party recommendations for interpreting atmospheric deposition data
- Evaluate spatial interpolation among shoreline sampling sites and evaluate potential attenuation of fluxes moving into Utah Lake
- Evaluate the chemical speciation of total nutrient atmospheric deposition loads
- Compare direct estimates of atmospheric deposition to other constraining analyses
- Determine atmospheric deposition loading estimates to Utah Lake

Analysis, Results, and Subgroup Decisions

Review and Summarize Data

Methods

Atmospheric deposition flux data were acquired from Gus Williams and Wood Miller. Data from Gus Williams included data from Olsen et al. 2018, Reidhead 2019, and Barrus et al. 2021. These two datasets represent data collected from two different sampler designs and are hence referred to as the "Williams" and "W. Miller" datasets.

Data were cleaned in an R script. The cleaned data were unchanged from the raw data in the excel spreadsheets, with the exception of compiling data from different sites into a single spreadsheet and adding columns for date information, conversions to flux per unit time. The Williams dataset included measurements listed as 0 mg/m^2, which were associated with non-detect concentrations of nutrients. The research team confirmed there was no method to convert a detection limit-based concentration to an area-based flux, so the values were retained as-is. The W. Miller dataset contained detection limit information, and non-detects were set at ½ the detection limit.

Decision Point: Assigning non-detect values

All Subgroup members agreed with assigning non-detect values at 0 mg/m^2 if there was not a method to convert a detection limit-based concentration to an area-based flux. Subgroup members discussed that there were relatively few samples in the Williams dataset listed at 0 mg/m^2, so there was little concern that retaining the values as-is would have a significant impact on the results when calculating the area-based flux for each site.

The Williams dataset was evaluated for outliers for each chemical constituent. Outliers were flagged if they exceeded the 75th percentile + 1.5*IQR from the whole dataset. IQR is the interquartile range, defined as the span between the 25th and 75th percentile. This approach has a potential drawback, as it may set a high threshold for outliers, and large deposition events may be obscured because they are not extreme enough. However, because flagging outliers was meant as an exploratory step rather than a firm rule that dictated an action to take with the data, the outlier identification approach was retained. Analyses in this document focus on areas around Utah Lake and thus include all sites from the W. Miller dataset and all sites except Central Davis Low and Ambassador, which were located near Salt Lake City.

Decision Point: Identifying outliers

The Subgroup members considered several potential methods for identifying outliers, including the IQR approach, an extreme value analysis, or the assignment of a specific flux as a cutoff for outliers. All Subgroup members agreed to identify outliers using the defined IQR approach. The rationale behind the decision was that the Williams dataset does not follow a normal distribution due to atmospheric deposition being episodic in nature. Since the Williams dataset does not follow a normal distribution, it is appropriate to identify outliers using the interquartile range since this method does not depend on the data following a normal distribution.

All Subgroup members also agreed to apply the IQR approach to the entire Williams dataset rather than on a site-by-site basis. This decision was made with the understanding that Subgroup members could later apply the IQR approach to identify outliers in site-specific datasets if there was interest in exploring specific locations more in-depth.

Lastly, all Subgroup members agreed to use the IQR approach to identify low and high outliers. The application of the IQR approach to identify low outliers yielded a range in which low outliers would have a negative value. Since it is not possible to have a negative atmospheric deposition value, the IQR approach did not result in the identification of any low outliers.

The decision on the approach to identify outliers was not a decision on whether to include outliers within the dataset. This decision was an exploratory step to help Subgroup members understand and discuss the data.

The nutrient deposition units for the Williams dataset were reported in mg/m^2, which were converted to $mg/m^2/d$ and $mg/m^2/wk$. Most samples were collected on weekly timescales, but this was not always the case. Thus, total accumulation over the sampling period was calculated for each sampling period by dividing the flux by the interval of each sampling period (daily flux) or the fractional week (weekly flux). The units reported in the W. Miller dataset were in mg/L. To convert the fluxes into comparable units between the studies, it was necessary to convert the volume-based concentrations in the W. Miller dataset to an area-based flux. Sample volumes were not reported for the W. Miller dataset, so the alternative was to identify precipitation amounts for each of the sampling periods. This approach was taken in the original report (W. Miller 2021) using precipitation from a single station at Lehi. The Science Panel Subgroup identified several precipitation samplers in the area surrounding Utah Lake and paired sampling stations with the nearest precipitation sampler (Table 1). The depth of precipitation accumulated over the course of a sampling event was calculated, and this value was used to convert volume to area for the flux values. Conversions were calculated using the relevant diameters of the sampler (collector: 20 in diameter; container: 4 in diameter).

Table 1. Weather stations located closest to each atmospheric deposition sampler. For most sites, a primary weather station located closest to the sampler and a secondary weather station located second closest to the sampler were identified. In the event there were gaps in the weather data for the primary weather station, data from the secondary weather station were substituted.

AD Station	Dataset	Primary Weather Station	Primary Station ID	Secondary Weather Station	Secondary Station ID
Orem	W. Miller	I-15 at Orem	UTORM	Provo Municipal Airport	KVPU
Orem	Williams	I-15 at Orem	UTORM	Provo Municipal Airport	KVPU
BYU	W. Miller	PROVO, BYU, UT US	USC00427064	Eyring Science Center	EYSC
Spanish Fork	W. Miller	SPANISH FORK POWER HOUSE, UT US	USC00428119	EW2355 Spanish Fork	UKBKB
Lake Shore	Williams	Lincoln Point	FG015		
Lincoln Point	W. Miller	Lincoln Point	FG015		
Bird Island	Williams	Lincoln Point	FG015		
Genola	W. Miller	Genola South	FG019	Genola	FG004
Elberta	W. Miller	Genola South	FG019	Goshen	FG014
Mosida	W. Miller	SR-68 at MP 16 Mosida	UTLAK	Genola	FG004
Mosida	Williams	SR-68 at MP 16 Mosida	UTLAK	Genola	FG004
Pelican Point	W. Miller	SR-68 at MP 16 Mosida	UTLAK	UTAH LAKE LEHI, UT US	USC00428973
Saratoga Springs	Williams	SR-68 at MP 16 Mosida	UTLAK	UTAH LAKE LEHI, UT US	USC00428973
Lehi	W. Miller	UTAH LAKE LEHI, UT US	USC00428973	Pioneer Crossing	UTPCR
Pump Station	Williams	UTAH LAKE LEHI, UT US	USC00428973	Pioneer Crossing	UTPCR

Decision Point: Converting W. Miller volume-based fluxes (mg/L) to area-based fluxes (mg/m^2)

Originally, an area-based flux based on the W. Miller dataset was estimated using the precipitation values from a single precipitation gauge. All Subgroup members agreed that calculating an area-based flux based on the W. Miller dataset would be more representative of local conditions if the sampling stations were paired with the data from the nearest precipitation sampler. Subgroup members used a map to identify the primary and secondary weather stations associated with each W. Miller sampling station to generate precipitation values to calculate an area-based flux.

Results

Williams Dataset

Large flux events for TP and DIN were typically associated with individual stations, usually Saratoga Springs, Lakeshore, and Mosida (Figure 1 through Figure 8). Some high flux events were observed at all sites, whereas others were observed at only one site. TP outliers were considered for samples exceeding 19 mg/m^2, which equated to between 2 and 3 mg/m^2/d, depending on the sampling interval. DIN outliers were considered for samples exceeding 108.21 mg/m^2, which equated to 15 mg/m^2/d, with variability depending on the sampling interval. The sampler collectors were screened starting on 2020-05-21. From Barrus et al. (2021), sampler screening was associated with significantly lower flux of both TP and DIN.

Data were also available and analyzed for nitrate, ammonium, and soluble reactive P (SRP) for the Williams dataset, but the report focuses on the total constituents for simplicity. Graphs of SRP, nitrate, and ammonium are provided in the Appendix.

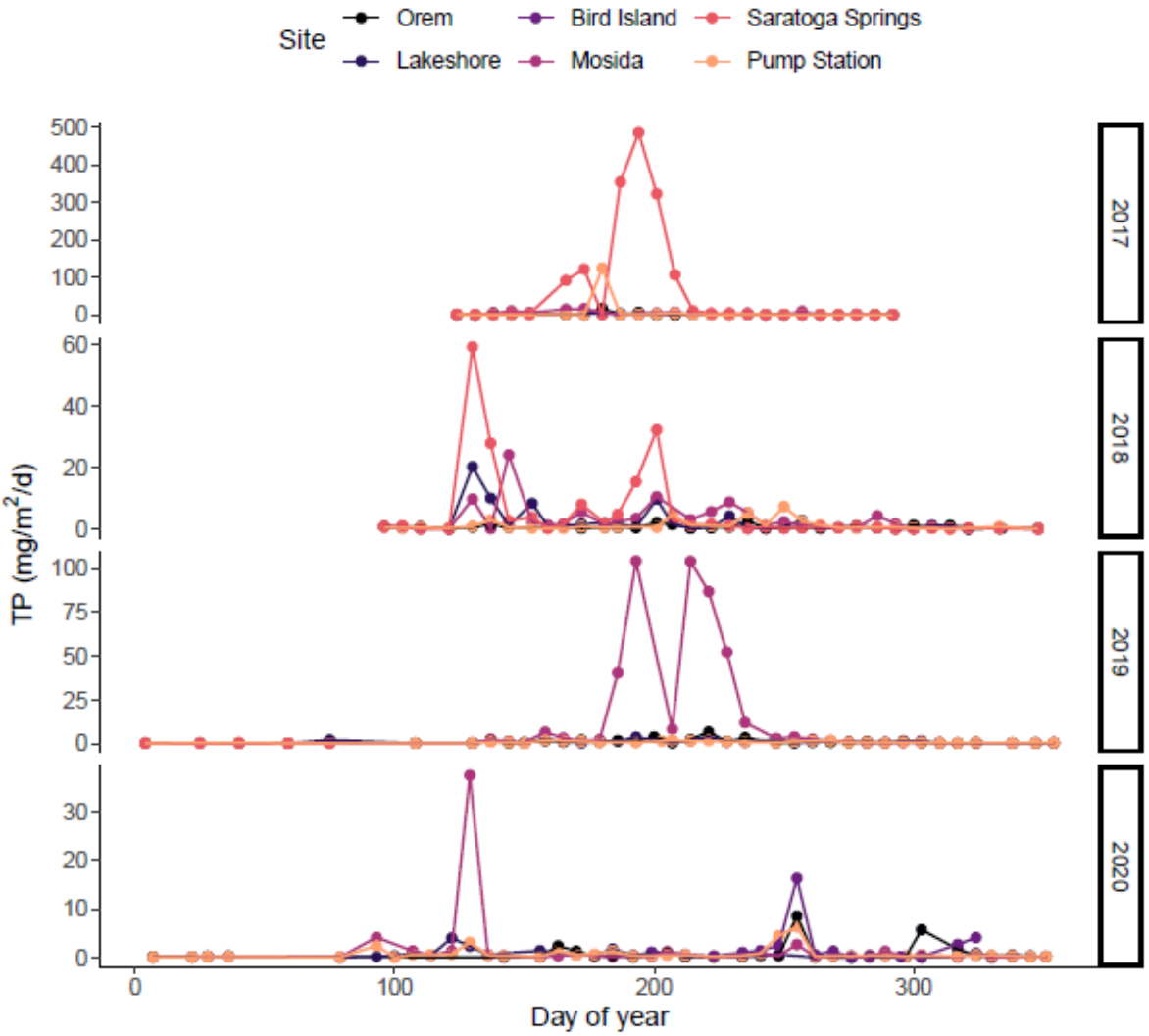

Figure 1. Time series of TP fluxes for the Williams dataset. Note the difference in y axis range for each year.

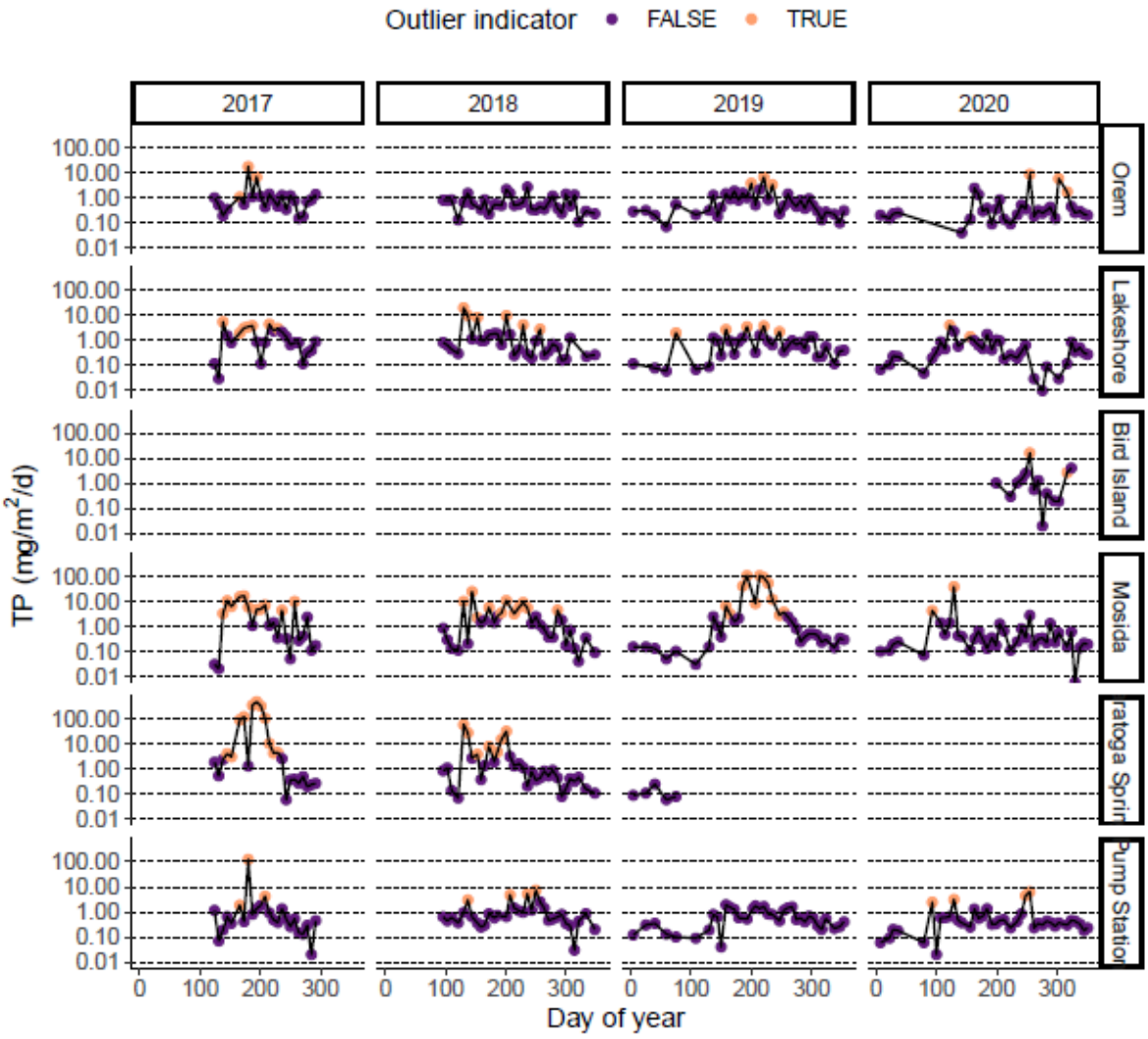

Figure 2. Time series of TP fluxes for the Williams dataset. Outliers are noted in orange.

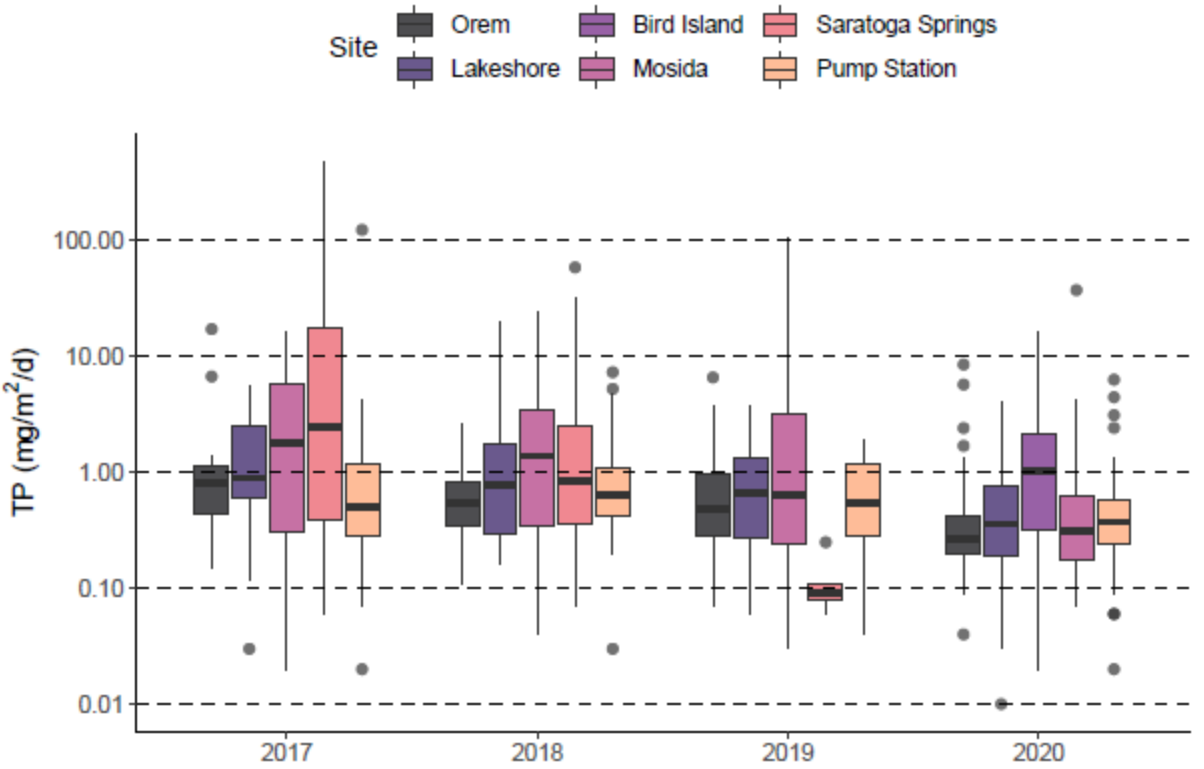

Figure 3. Boxplots of TP fluxes for the Williams dataset.

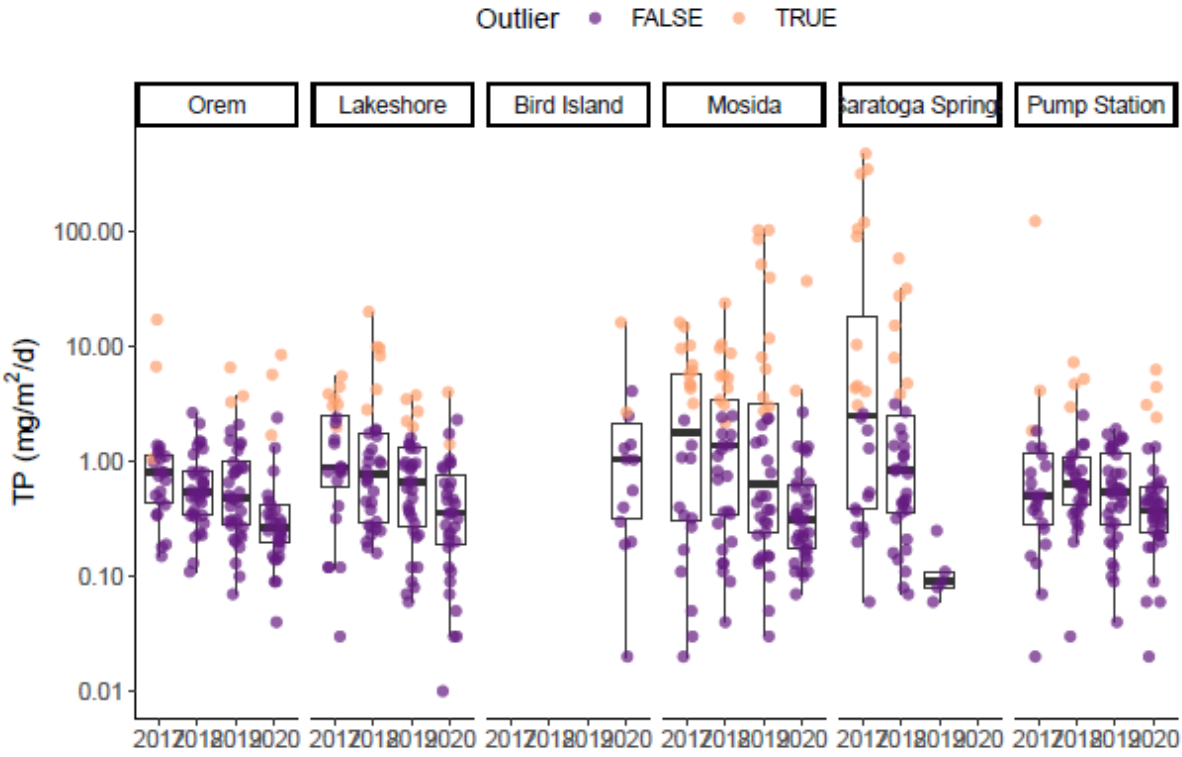

Figure 4. Boxplots of TP fluxes for the Williams dataset, with individual samples marked as points. Outliers are noted in orange.

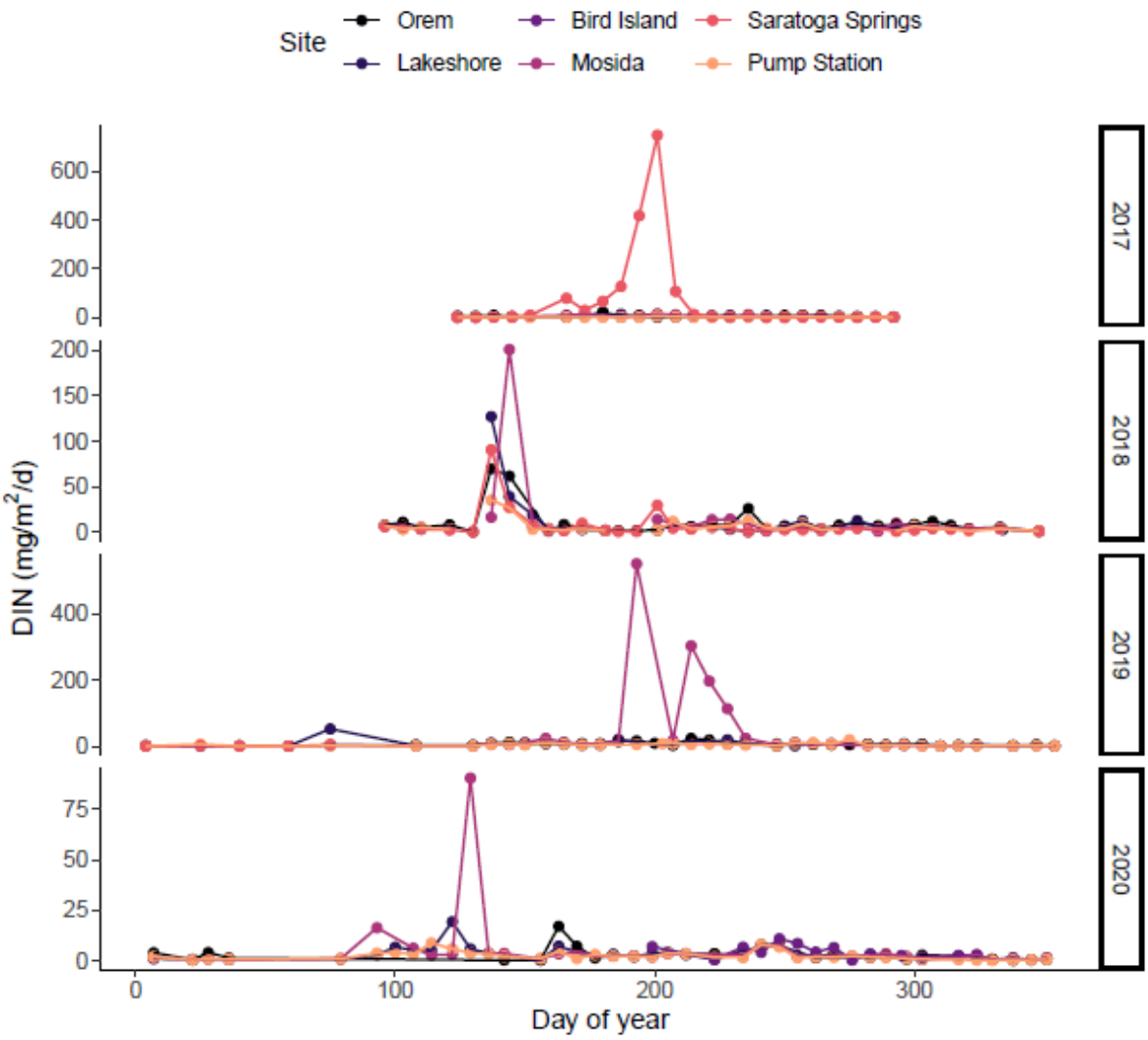

Figure 5. Time series of DIN fluxes for the Williams dataset. Note the difference in y axis range for each year.

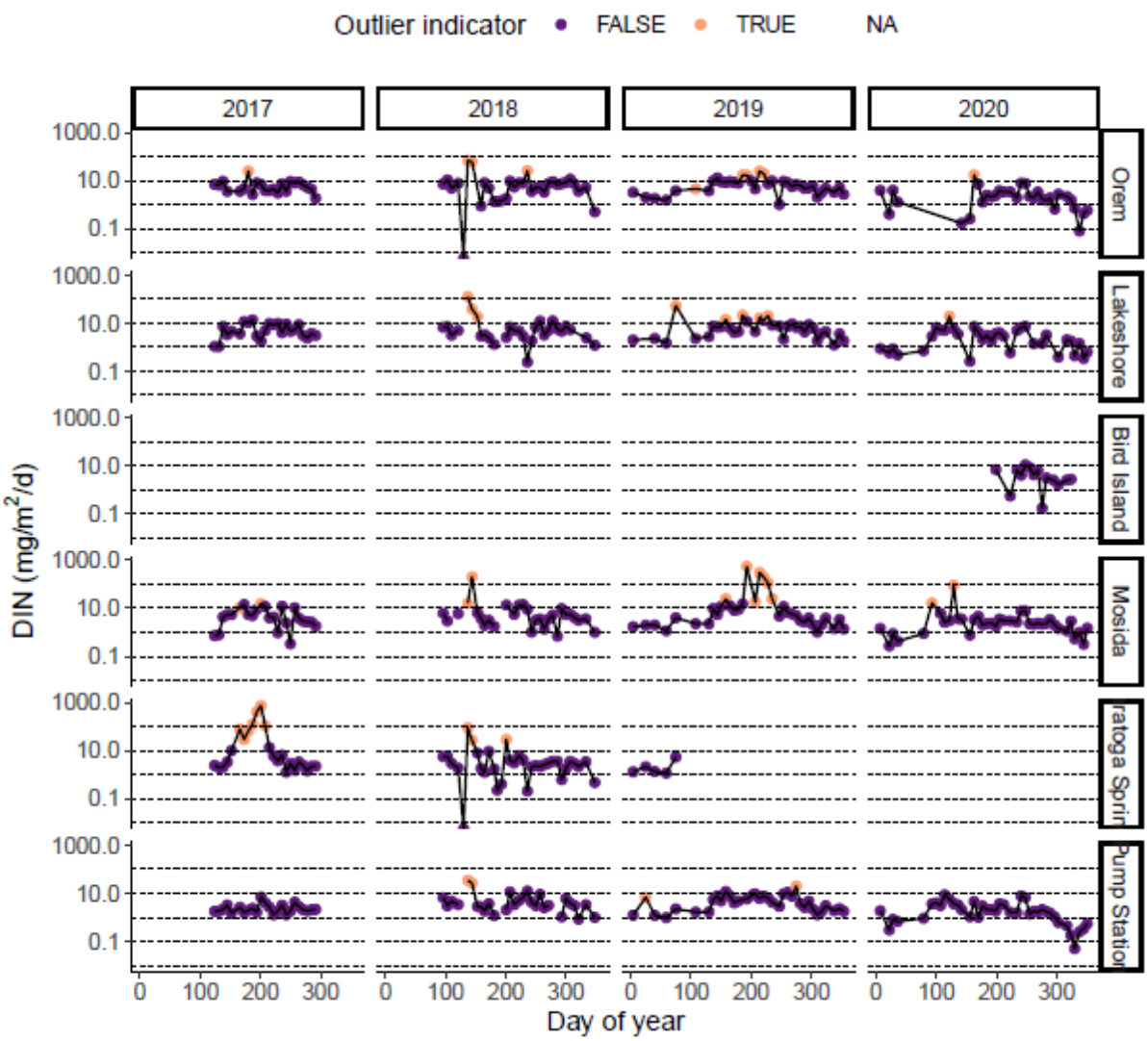

Figure 6. Time series of DIN fluxes for the Williams dataset. Outliers are noted in orange.

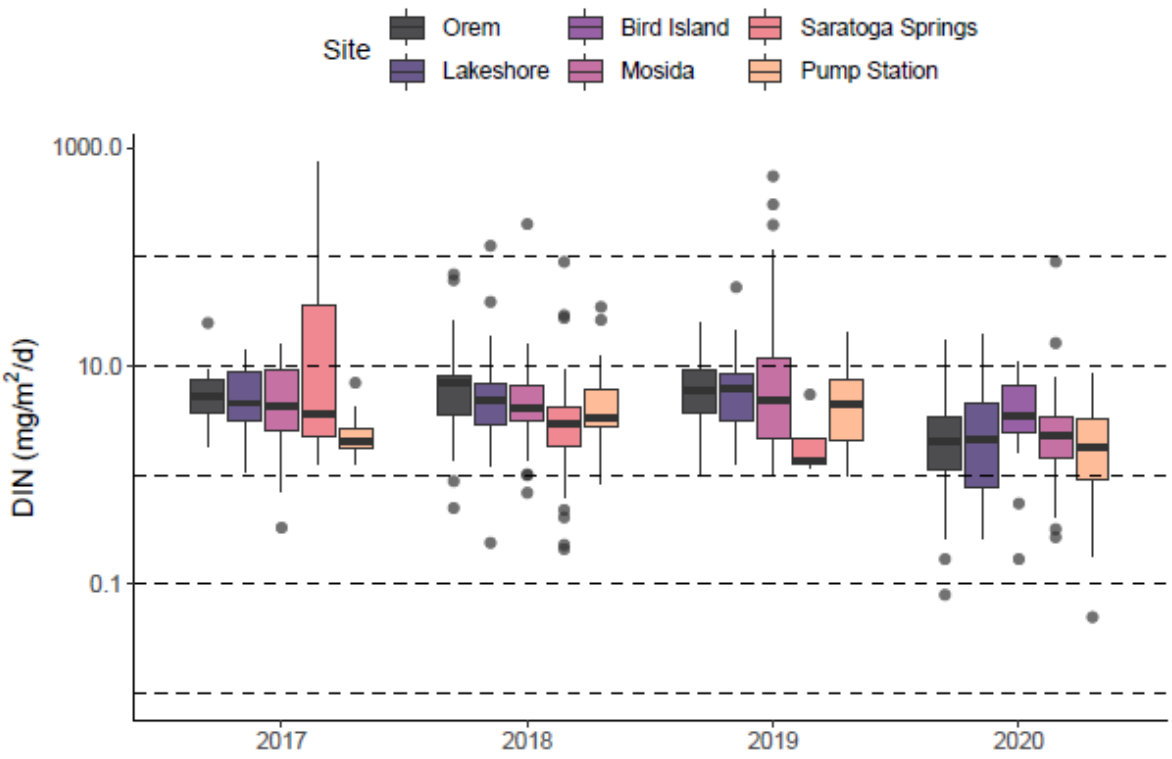

Figure 7. Boxplots of DIN fluxes for the Williams dataset.

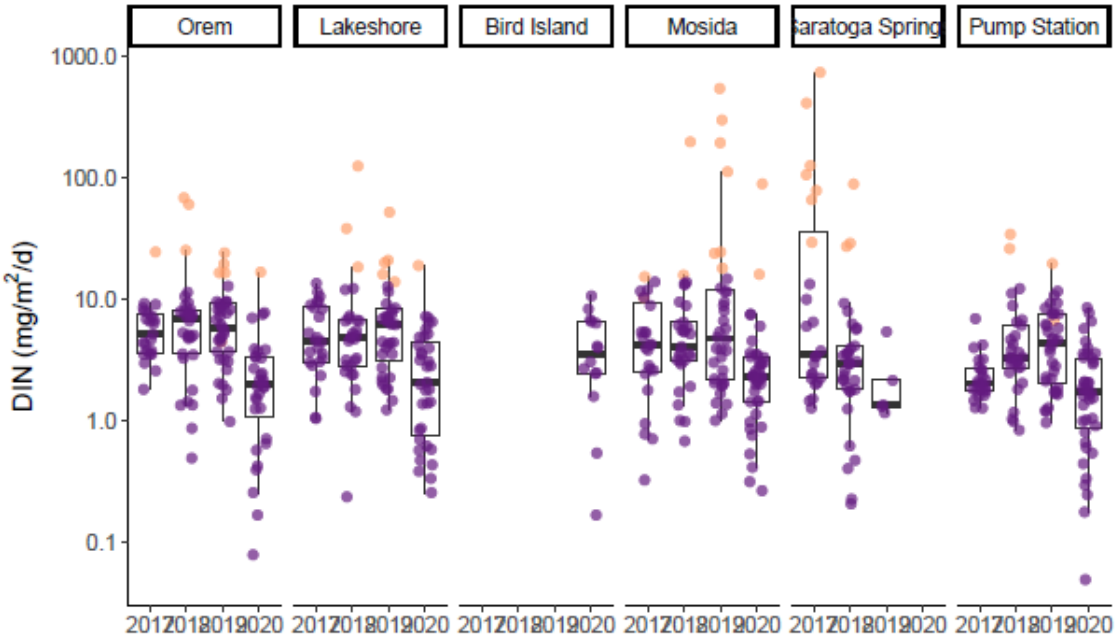

Figure 8. Boxplots of DIN fluxes for the Williams dataset, with individual samples marked as points. Outliers are noted in orange.

The interval between sampling events did not appear to impact flux. Specifically, samples taken on an interval longer than one week were not associated with systematically higher or lower fluxes than weekly samples (Figure 9, Figure 10).

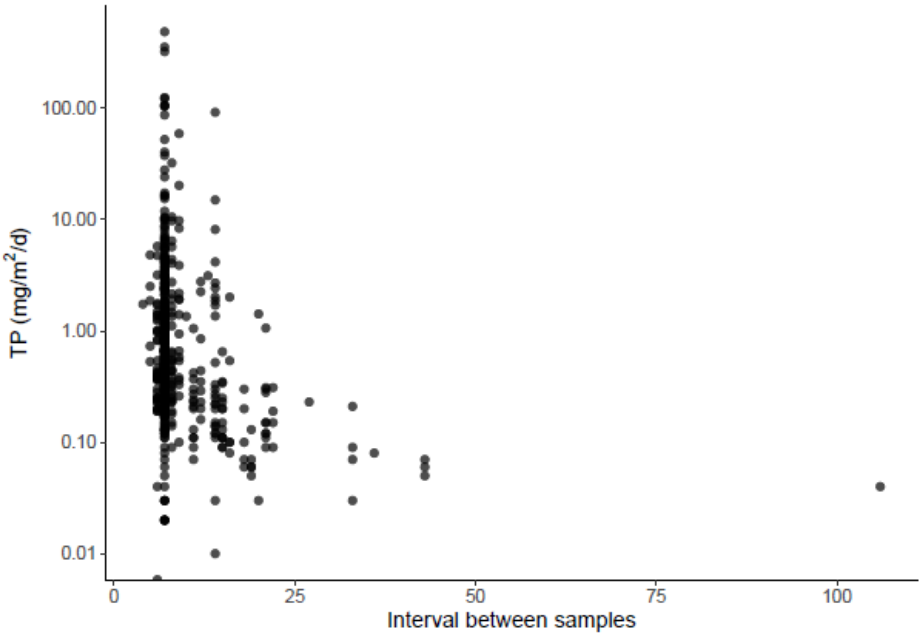

Figure 10. Relationship between TP flux and sampling interval for the Williams dataset.

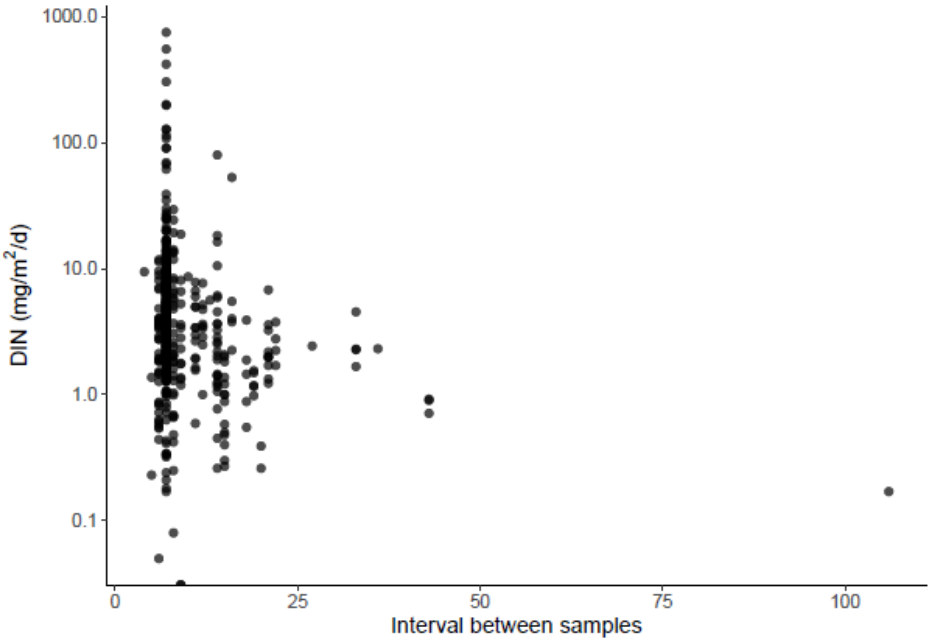

Figure 9. Relationship between DIN flux and sampling interval for the Williams dataset.

W. Miller Dataset

Large flux events for TP and TN were typically associated with individual stations rather than being consistent across stations (Figure 11, Figure 12). Several sampling events were associated with large time gaps, and no metadata was provided to determine whether samplers were deployed the entire time or cleaned between sampling events.

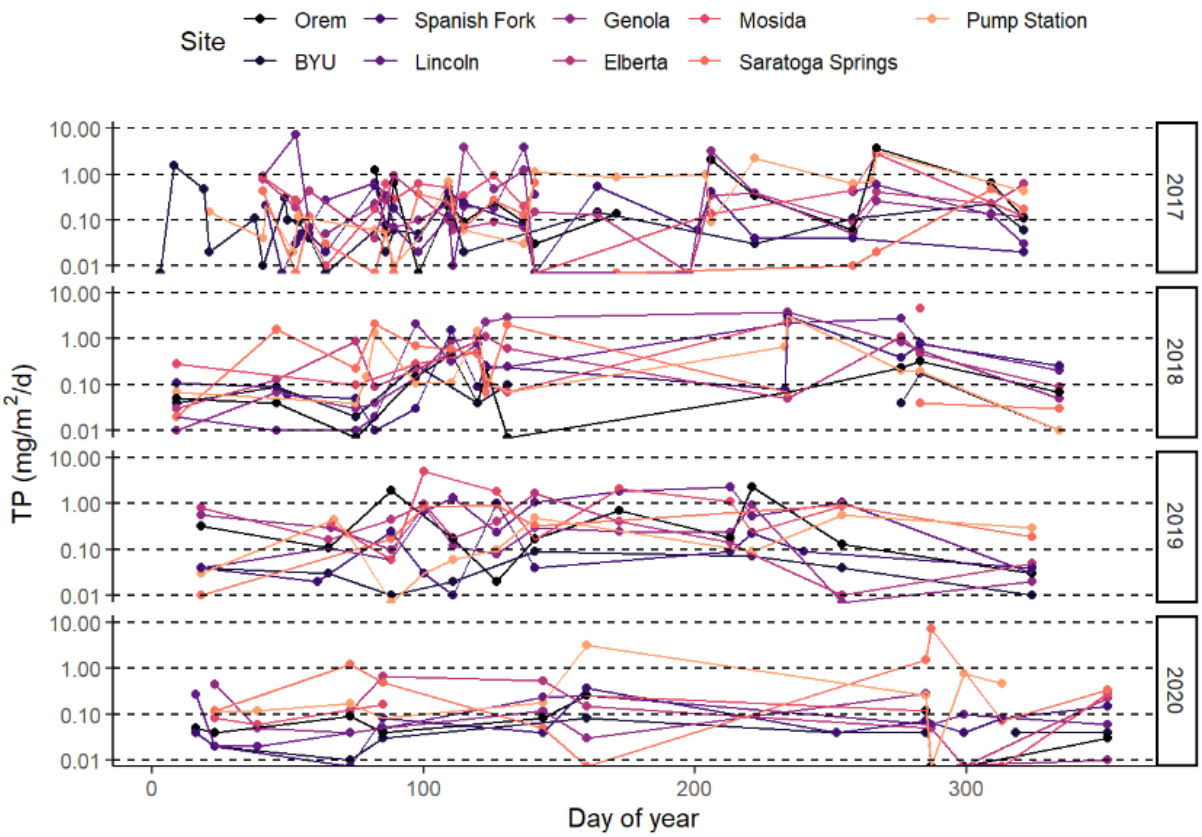

Figure 11. Time series of TP fluxes for the W. Miller dataset.

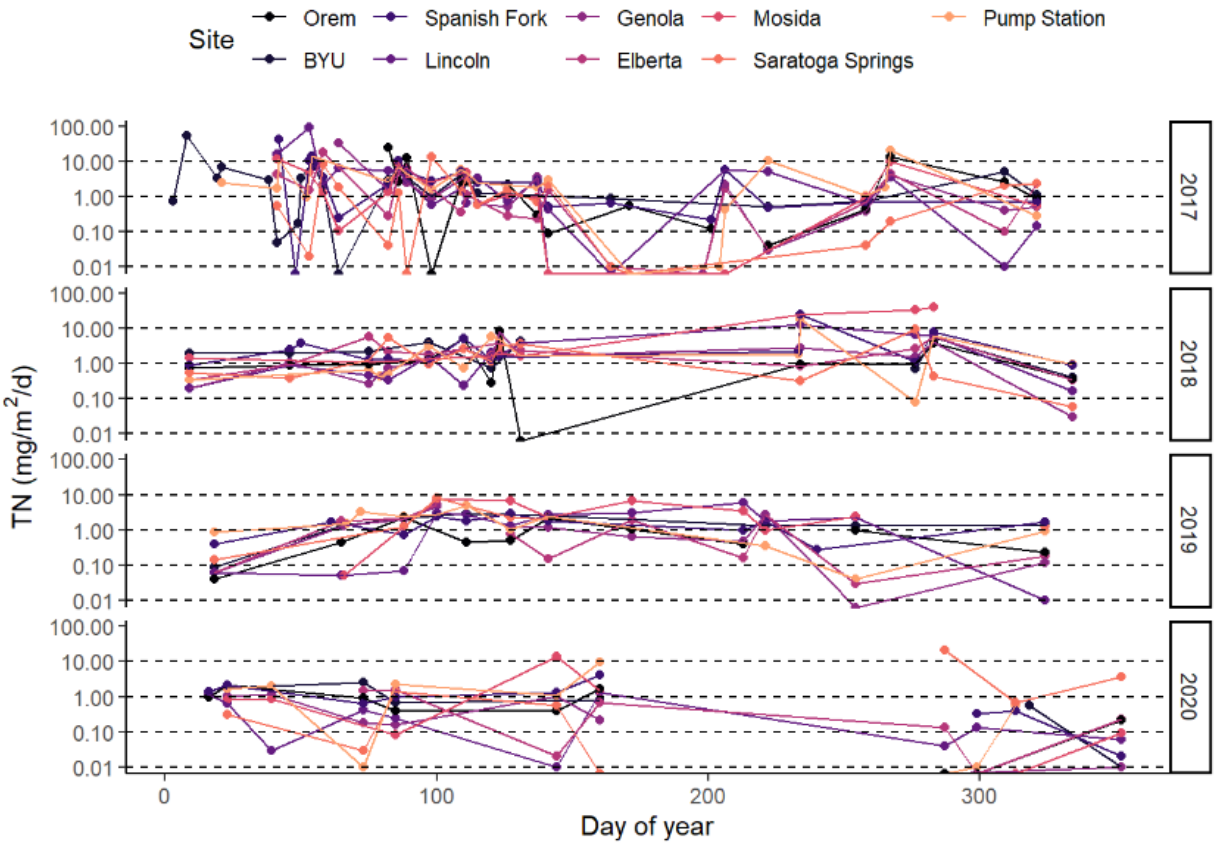

Figure 12. Time series of TN fluxes for the W. Miller dataset.

Evaluate outlier samples for potential explanations

Review of previous Science Panel and third-party recommendations

High outlier fluxes could be a function of several possibilities: (a) presence of materials such as insects, (b) influence of local nutrient sources, or (c) influence of high deposition events such as wind or rain storms. Previous studies, Science Panel recommendations, and external reviews from Dr. David Gay addressed item (a), the presence of materials such as insects. Olsen et al. (2018) labeled a sample as "contaminated" if samplers had visible contamination (bird droppings, insects, plant matter, and algal growth). The authors detail,

> *"The largest dry deposition rates occurred at Saratoga Springs during the summer months with rates significantly higher than any of the other sites (see Figure 4). We attribute some of these high values to a terrestrial bee, Halictidae Lasioglossum. During the summer period, sample buckets had numerous bee bodies in the water. As noted above, these bodies were removed before sample analysis, but having been present in the water during the week, they significantly raise the amount of nutrients in the samples."*

This study found that loading values associated with contaminated samples were 44 and 10 times higher for TP and DIN loads, respectively, than loading values associated with uncontaminated samples. Barrus et al. (2021) also noted a high prevalence of insects in samplers, particularly at the Mosida location in the summer months. The majority of high outlier samples in Barrus et al. (2021) were associated with large numbers of visible insects in the samples. TP and DIN fluxes were significantly higher in samplers that were not equipped with screens (which kept insects from entering the sample) than in samples equipped with 500 µm screens (paired t-test; TP: avg. difference in means = 0.36 $mg/m^2/d$, $p < 0.0018$, DIN: avg. difference in means = 0.26 $mg/m^2/d$, $p < 0.0116$). Richards (2022) also noted that screened samplers had significantly lower fluxes than unscreened samplers (mixed effects negative binomial regression; TP: difference in means at Orem = 8.43 mg/m^2, $p < 0.01$; DIN: difference in means at Orem: 22.1 mg/m^2, $p < 0.001$).

In Science Panel Comments Regarding Wasatch Front Water Quality Council's Atmospheric Deposition Study (from August 1, 2019), it was noted that midge biomass (and presumably other insect biomass) should not be considered an atmospheric deposition flux to Utah Lake. Though insect biomass moving into or out of the lake may represent a source or sink of nutrients, it was recommended that any insect flux should be considered separate from rates of atmospheric deposition. Finally, in David Gay's feedback on the sampling and analysis plan for the Williams study (December 24, 2019), he detailed "It seemed to be the consensus of all the groups that insects be excluded from the wet deposition samples and internal/external cycling of these insect analytes be treated separately."

Decision Point: Considering insects as contamination

Subgroup members discussed whether insects or insect parts in sampling buckets should be considered contamination. Subgroup members did not reach a consensus on this decision point.

The majority of Subgroup members agreed that insect or insect parts in sampling buckets should be considered contamination. The Subgroup members that agreed with this perspective acknowledged that terrestrial insects do fall onto the surface of large lakes, but any insects or insect parts found in samplers are not likely representative of their contribution to the lake. Additionally, the Subgroup members in the majority stated that there is uncertainty about whether insects in the sampling buckets are terrestrial or aquatic in origin. Terrestrial insects are not part of the Utah Lake system, so their parts in a sampling bucket would be considered a net influx. Since aquatic insects are a part of the Utah Lake system, their parts in the sampling bucket would not a represent a net influx of nutrients to the lake. If insects are considered important to the nutrient budget of Utah Lake, the Subgroup members suggested there be a study intentionally designed to provide a better estimate of the influx and efflux of insects to Utah Lake.

One Subgroup member did not agree with the majority of the Subgroup. Their perspective was that insects should not be considered contamination in the sampling buckets. Their rationale was that insects contribute to the nutrient budget of Utah Lake and should be considered a legitimate nutrient source in the analysis.

Methods

To separate the potential causes of high outlier fluxes (see a-c above), field metadata were reviewed for the Williams dataset. Metadata were previously made available by Jacob Olsen for the 2017 data, and metadata were provided for the 2020 data. These metadata identified insect and plant matter presence in samples (Table 2). If a sample contained insect matter, it was considered contaminated per Science Panel recommendations. 2018 and 2019 data did not have metadata available, and according to Science Panel recommendation those data were removed from consideration because contamination could not be definitively ruled in or out.

Table 2. Details about the data available for each dataset.

Study	Year(s)	Number of stations	Constituents	Sample type	Metadata availability
Williams	2017	5	TP, DIN, nitrate, ammonium, SRP	Bulk	Yes
Williams	2018	5	TP, DIN, nitrate, ammonium, SRP	Bulk	No
Williams	2019	5	TP, DIN, nitrate, ammonium, SRP	Bulk	No
Williams	2020	5	TP, DIN, nitrate, ammonium, SRP	Bulk	Yes
W. Miller	2017-2020	9	TP, TN, orthophosphate	Bulk	No

Decision Point: Request for metadata and how to handle data without metadata

Subgroup members requested available metadata on the atmospheric deposition data from the Williams dataset. Theron Miller and Gus Williams searched their records and reached out to the graduate students who collected data from the samplers. They provided metadata for the Olsen (2019) dataset through November 2017 and the Barrus (2020) dataset. The metadata for Reidhead (2020) was not available.

Subgroup members discussed how to incorporate data points from the Williams dataset if metadata is not available. All Subgroup members supported using atmospheric deposition data if either of the following conditions is true:

- The atmospheric deposition data were collected from a sampler with a screen installed
-There is metadata available, and the metadata indicates insect or insect parts were not in the sample

Furthermore, insofar as insects are considered contamination, a decision that did not reach a consensus among the Subgroup, Subgroup members supported the approach that if the metadata indicates that a sample has insect or insect parts in it, those samples will be excluded from the analysis.

The rationale for this approach is that screens on the samplers keep insects out of the sample. For samples where metadata is available, the metadata gives Subgroup members confidence that insects or insect parts were not found in the samples. For samples without metadata, there is uncertainty on whether insect or insect parts affected the measured N and P values in the samples.

One Subgroup member suggested that the Subgroup only use screened data for the analysis and exclude any unscreened data with or without metadata. Subgroup members indicated that they had confidence in the screened data, so an approach that only incorporates screened data would simplify the analysis. Subgroup members discussed that one challenge with this approach is that there is only screened data for half a year. It would be difficult to extrapolate an annual flux based on the data, given that seasonal impacts on atmospheric deposition may not be captured with only a half-year worth of data. Ultimately, Subgroup members elected to use a dataset that included 1) data from screened samplers and 2) data from unscreened samplers where the metadata indicates that there were no insect parts in the sample.

Results

The majority of outliers were contaminated, and the majority of non-outliers were not contaminated (ignoring unknown samples) (Figure 13, Figure 14). When comparing contaminated and uncontaminated samples, TP flux was significantly higher in contaminated samples (ANOVA, $p < 0.0001$, $df = 275$; Figure 15). Among uncontaminated TP samples, there was no significant difference among sites (ANOVA, $p = 0.33$, $df = 169$). DIN flux was significantly higher in contaminated samples than uncontaminated samples (ANOVA, $p < 0.0001$, $df = 275$; Figure 16). Among uncontaminated samples, there was no significant difference among sites (ANOVA, $p = 0.25$, $df = 169$).

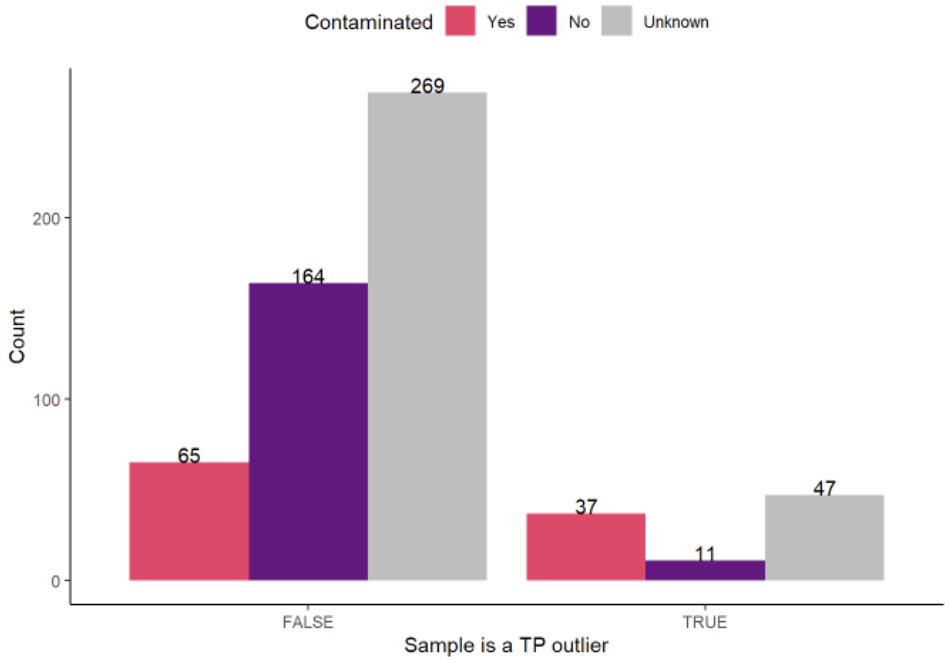

Figure 14. Counts of contaminated, uncontaminated, and unknown (i.e., no metadata available) TP samples in the Williams dataset, divided by whether the sample was an outlier.

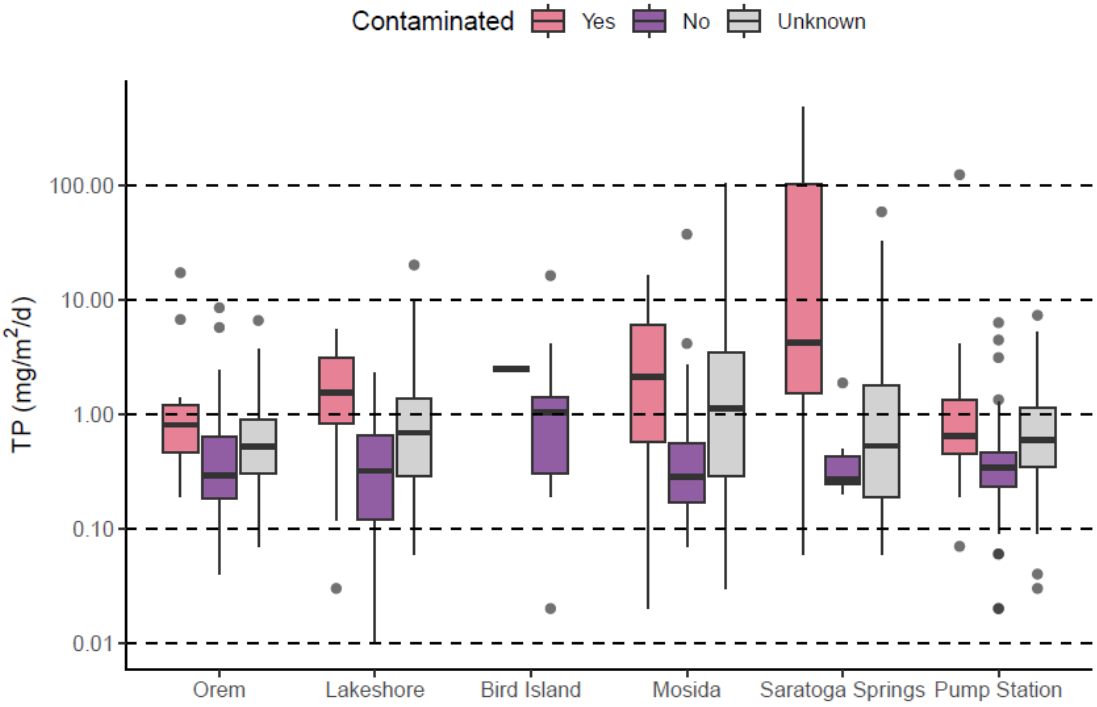

Figure 13. Counts of contaminated, uncontaminated, and unknown (i.e., no metadata available) DIN samples in the Williams dataset, divided by whether the sample was an outlier.

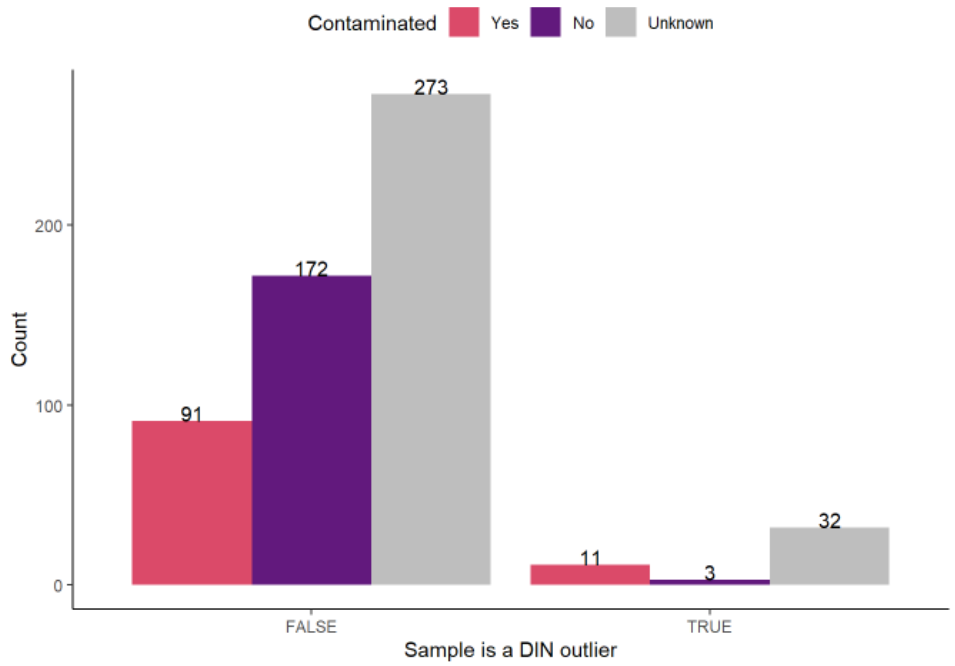

Figure 16. Boxplots of TP flux in the Williams dataset, divided by samples that were contaminated, uncontaminated, and unknown (i.e., no metadata available).

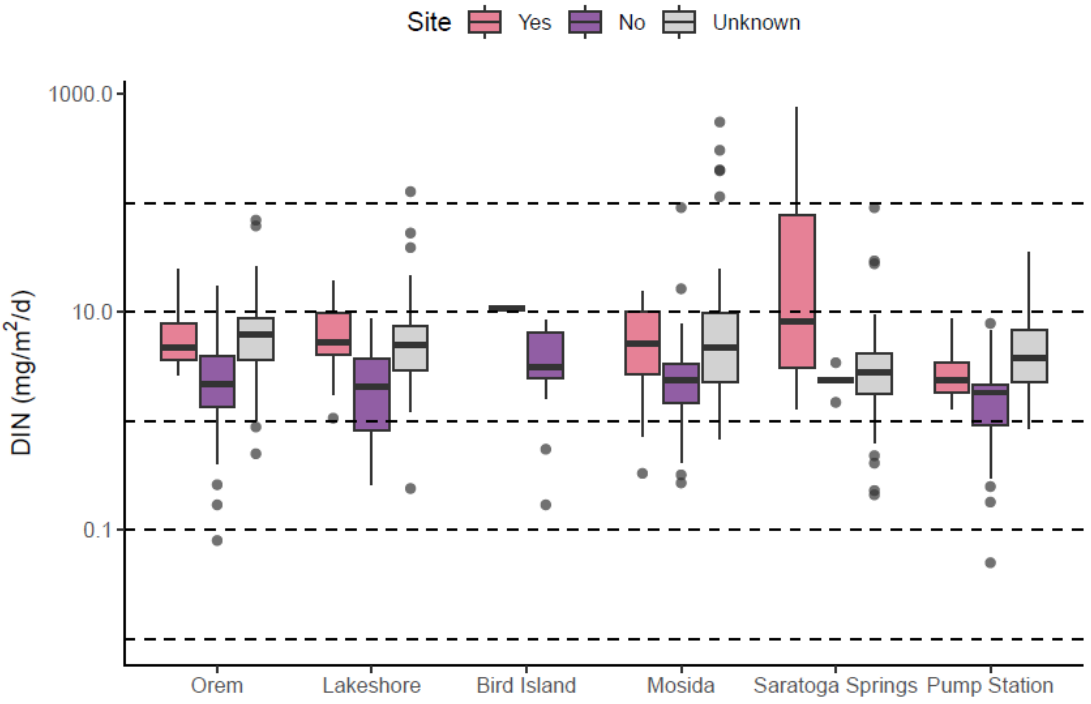

Figure 15. Boxplots of DIN flux in the Williams dataset, divided by samples that were contaminated, uncontaminated, and unknown (i.e., no metadata available).

Figure 17 through Figure 20 include flux for uncontaminated samples, either those confirmed to have no contamination or those collected after screen installation (2020-05-21). The majority of

outliers were associated with contaminated samples, but some remain in the 2020 dataset (open circles). These outliers could be associated with local sources and/or deposition events.

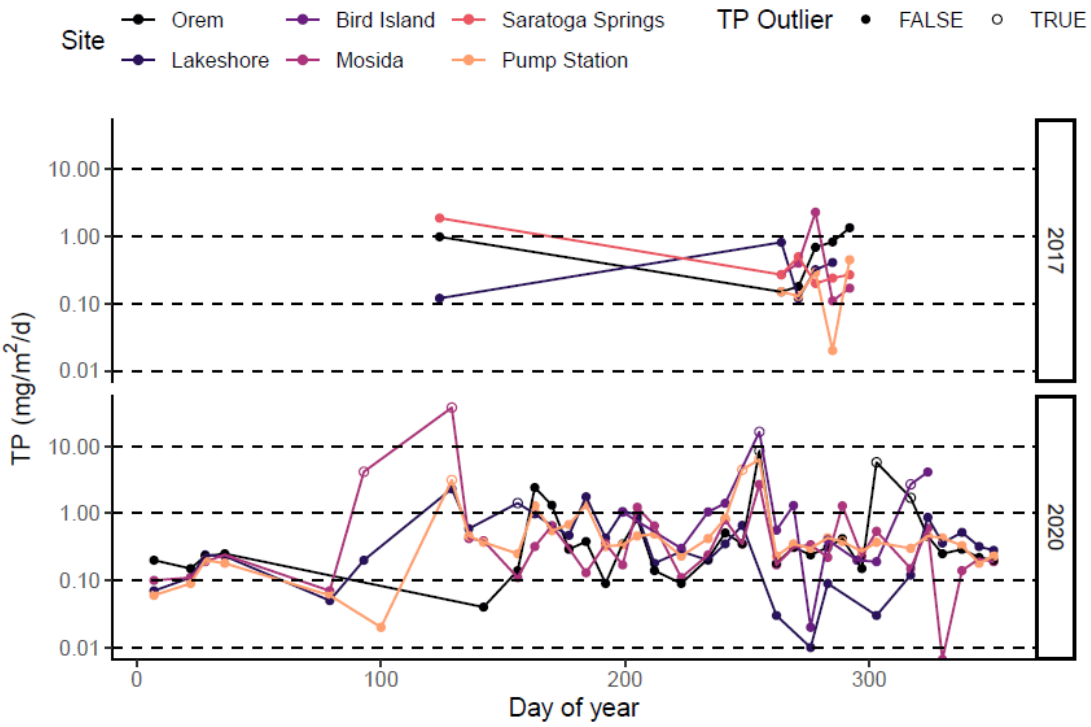

Figure 17 Time series of uncontaminated TP samples in the Williams dataset.

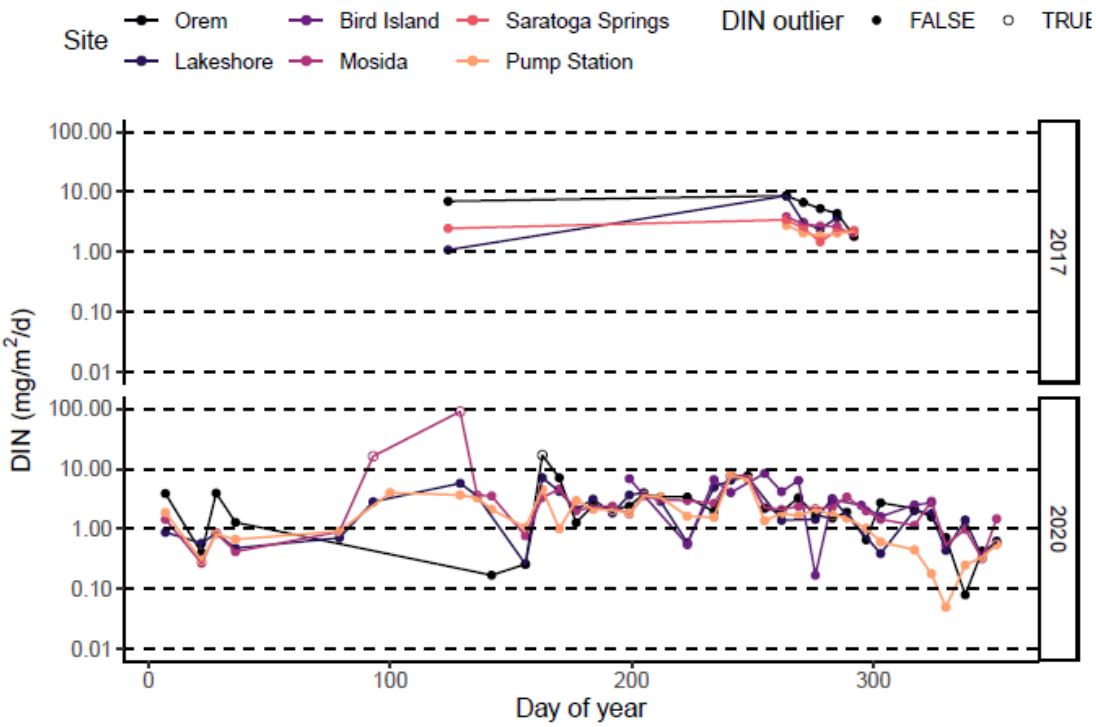

Figure 18. Time series of uncontaminated DIN samples in the Williams dataset

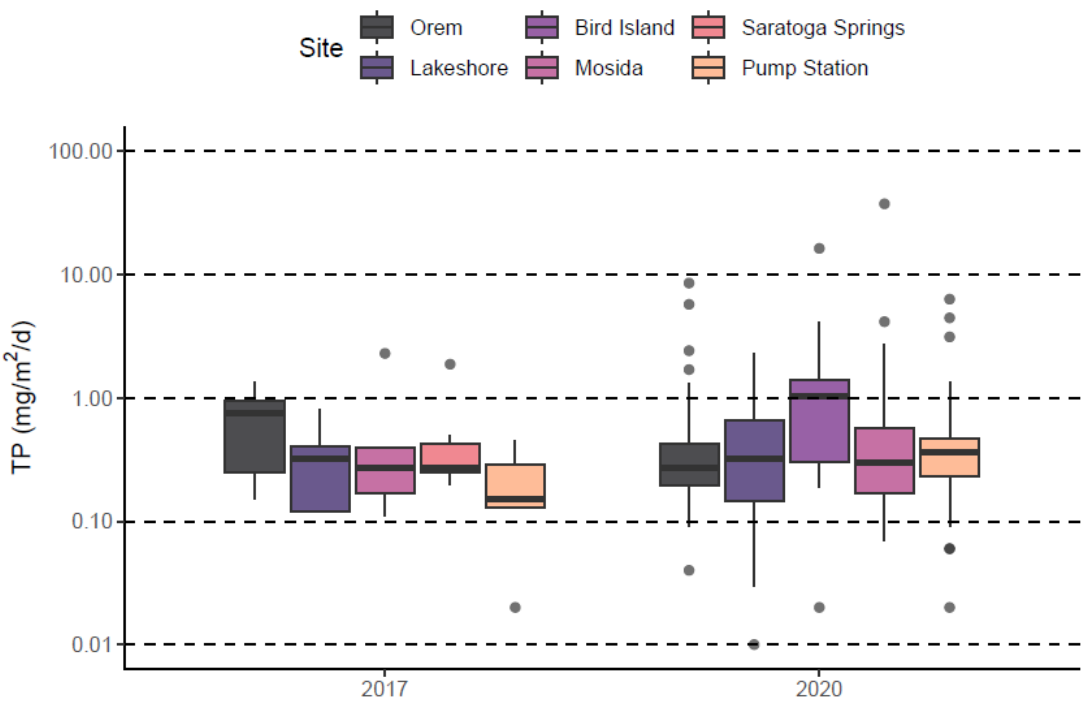

Figure 19. Boxplots of uncontaminated TP samples in the Williams dataset.

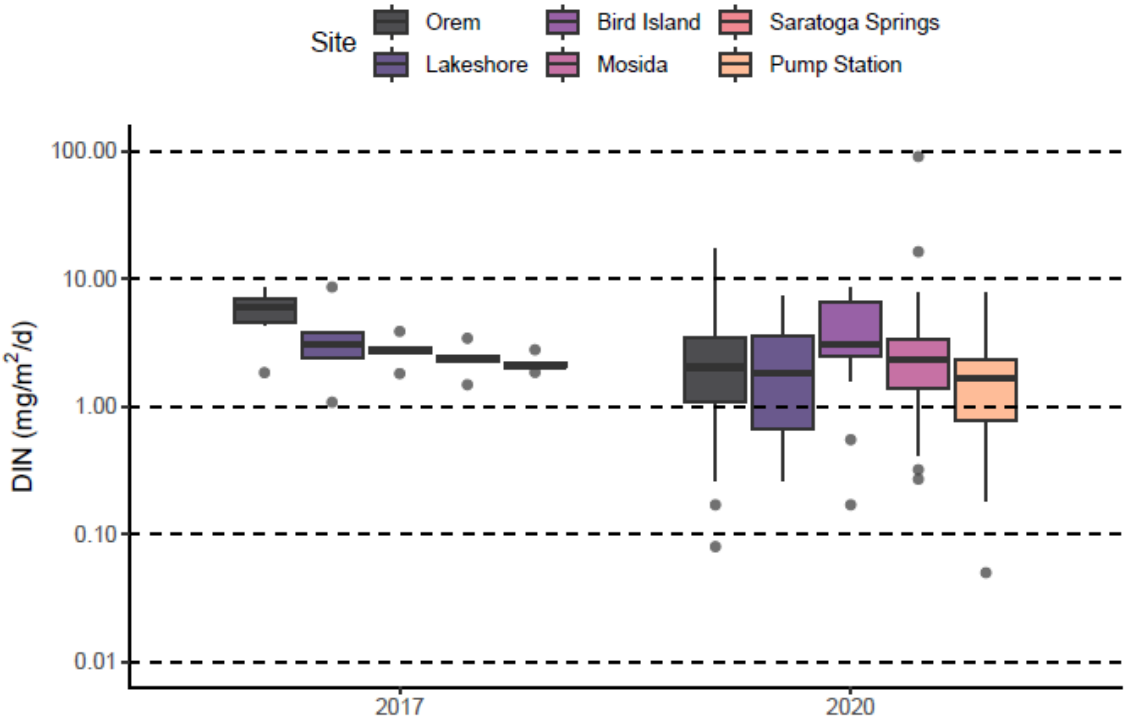

Figure 20. Boxplots of uncontaminated DIN samples in the Williams dataset.

Imputing flux estimates

Methods

Following removal of contaminated samples, gaps between sampling events were present in the time series, preventing the calculation of a cumulative annual flux. To fill in the gaps of sampled dates, two options were considered:

1. **Impute via linear interpolation.** If a missing sampling date is located equidistant from two other sampling dates that have data, the missing date would be assigned as the midpoint between the values of the two sampled dates. If the missing date was closer in time to one of the sampling dates, the imputed value would be proportionally closer to the closer date than to the farther date. Colloquially, this method could be defined as "connect the dots," like what is displayed in Figure 17 and Figure 18. This method assumes that missing data fall within the range of existing data, and values within a time series are related in time.
2. **Impute via relationships with weather.** Develop statistical relationships with weather patterns such as precipitation and wind and estimate likely flux values for missing sampling dates using the defined statistical relationship and the observations of weather during the sampled period.

To develop the statistical model for defining flux relationships with weather, data were compiled for:

- Average daily precipitation throughout sampling period
- Average & maximum PM2.5 throughout sampling period
- Average & max PM10 throughout sampling period
- Average of daily average wind speed throughout sampling period
- Max of daily average wind speed throughout sampling period
- Average peak daily wind gust throughout sampling period
- Max of peak daily wind gust throughout sampling period
- Month (as factor)

The weather stations located nearest the sampling stations were used, per Table 1. Weather stations included precipitation and wind data. Additional data on PM2.5 and PM10 were obtained from the Purple Air website at the West Mountain Ranch sampling location (https://www2.purpleair.com/). Stepwise model selection for multiple linear regression was run to determine the best subset of the potential predictor variables.

Decision Point: Imputing flux values for sampling dates removed due to contamination

Subgroup members discussed how to impute atmospheric deposition values in between sampling events. Due to the Subgroup's decision to exclude samples where metadata shows insects or insect parts present in the sample, some sampling events were removed from the dataset. The removal of the data left gaps between sampling events. Over several meetings, the Subgroup discussed two approaches to filling in the data between sampling events: a) imputing data via linear interpolation or b) imputing data via the results of the weather regression analysis. To help evaluate which approach is more appropriate given the dataset, all Subgroup members requested that Tetra Tech calculate the annual cumulative flux using a linear interpolation approach and the weather regression analysis to impute values for missing data.

After calculating the annual cumulative load using both approaches, Subgroup members discussed which approach is better suited to interpolate data between sampling events. As part of the discussion, they identified the benefits and drawbacks of linear interpolation. One of the benefits of linear interpolation is that it is a simple method for imputing data. One of the drawbacks of linear interpolation is that it assumes consistent and predictable patterns between sampling events, so it is not an effective method to capture patterns for episodic time series.

As a potential alternative method, Subgroup members discussed the approach for imputing data via the results of the weather regression analysis. With support from the Subgroup, Tetra Tech conducted a weather regression analysis between weather variables (e.g., precipitation, wind speed, PM2.5, and PM10) and atmospheric deposition values in the Williams dataset. Subgroup members also examined the relationship between precipitation and average wind speed and specific outliers at Mosida.

After reviewing the results of all the analyses conducted by Tetra Tech at the request of the Subgroup members, they agreed to use the results of the weather regression to impute missing values within the dataset. The rationale behind the decision was that applying a linear interpolation approach assumes a consistent and predictable pattern between sampling events. Since the atmospheric deposition time series is episodic, linear interpolation is not an appropriate method for imputing values. Since the weather regression analysis showed a relationship between weather variables and atmospheric deposition values, all Subgroup members supported using the results of the weather regression to estimate missing values between sampling events.

Results

Weather patterns tended to be fairly episodic and were often inconsistent among sites (Figure 21). Though episodic events were prevalent across the time series, the period from July through August tended to have fewer higher precipitation and wind events than other months in 2020. High deposition events were often preceded by high precipitation and/or wind events.

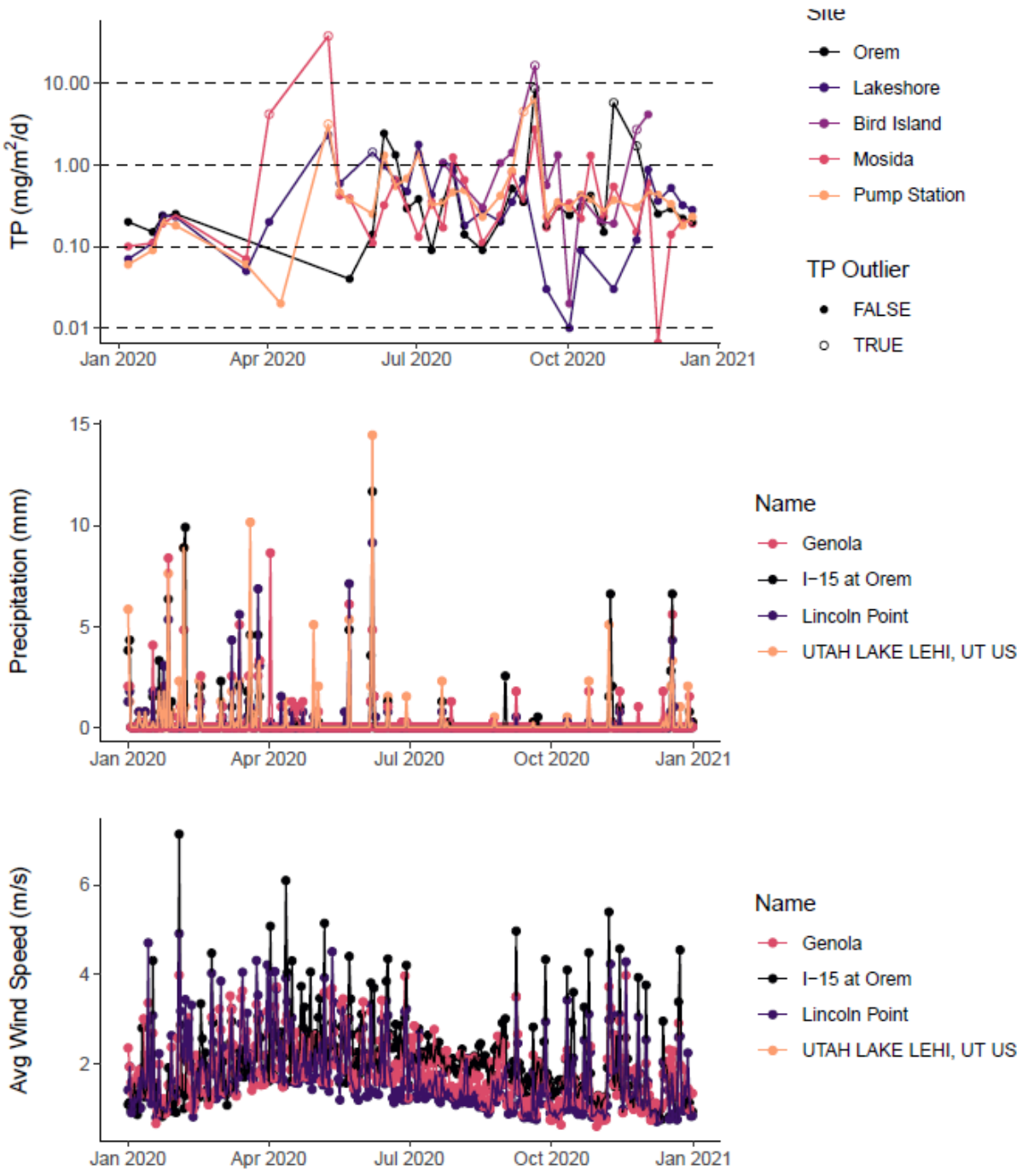

Figure 21. Precipitation and average daily wind speed at the weather stations associated with the atmospheric deposition sampling sites in the Williams dataset. TP fluxes for the same time period are displayed for additional context.

For TP fluxes, model selection indicated the average peak daily wind gust and maximum of peak daily wind gust were the best subset of predictors (Table 3). For DIN fluxes, model selection indicated the average daily precipitation, average PM2.5 and PM10, average peak daily wind gust, and maximum of peak daily wind gust were the best subset of predictors. These models supported the hypothesis that weather events such as high wind and precipitation drive high atmospheric deposition events (Table 3). Note that month was not a significant predictor for TP or DIN. The linear regressions did not fully explain the variability in flux, suggesting that (a) the integrated nature of the sampling periods (1+ weeks) did not allow for a detailed investigation at shorter timespans, and/or (b) weather data do not illuminate the full context of the drivers of atmospheric deposition, such as local sources and wind direction and temporal pattern.

Table 3. Multiple regression results to predict atmospheric deposition fluxes from weather conditions.

Response Variable	df	R^2	Coefficient: Avg. peak daily wind gust	Coefficient: Max. wind gust	Coefficient: Avg. daily precip.	Coefficient: Avg. PM2.5	Coefficient: Avg. PM10
TP	106	0.12	0.176	-0.045			
DIN	93	0.40	0.188	-0.088	0.296	0.657	-0.604

When gaps in sampling dates were filled via the weather regression, the calculated cumulative flux was lower than that estimated from linear interpolation for the Mosida and Lakeshore sites and was equivalent for the Pump Station and Orem sites (Table 4, Figure 22, Figure 23). The explanation for the cumulative flux being lower for the weather regression method than for linear interpolation was that the sampling periods associated with gaps tended to be "calm" periods of weather (i.e., fairly low wind and precipitation) that resulted in lower flux estimates than those generated from linear interpolation between sampling periods with relatively high observed fluxes.

Table 4. Cumulative annual fluxes for 2020 from the Williams dataset, with missing sampling dates imputed via weather regression relationship.

Dataset	Site	TP Cumulative Flux ($mg/m^2/y$)	DIN Cumulative Flux ($mg/m^2/y$)
Williams	Lakeshore	150.0	740.8
	Mosida	444.5	1,624.5
	Orem	203.5	735.5
	Pump Station	235.5	764.2

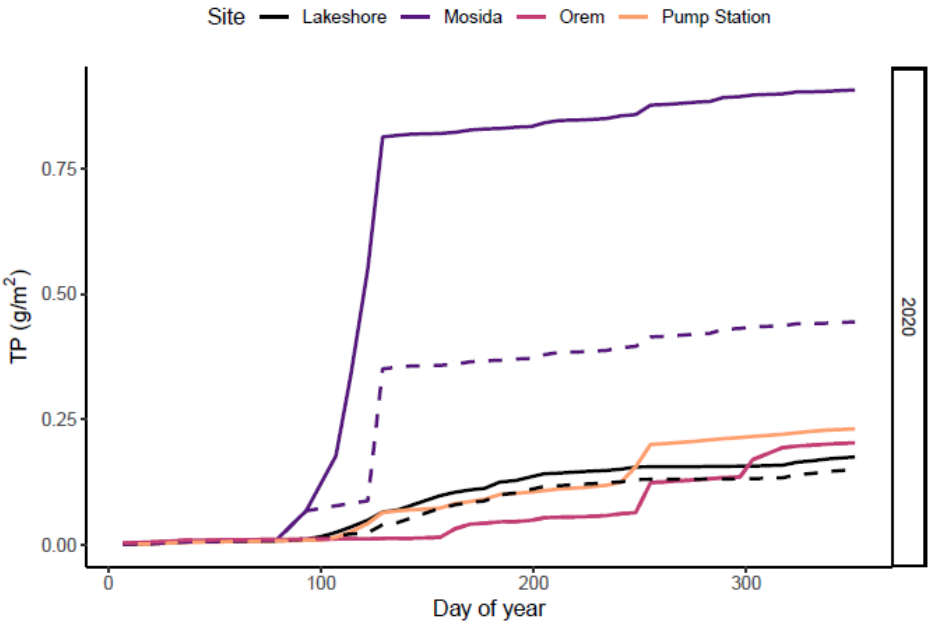

Figure 22. Cumulative TP flux for the Williams dataset, with gaps in sampling dates imputed by linear interpolation (solid lines) and weather regression (dotted lines). Note that the two imputation approaches were equivalent for Orem and Pump Station, so the solid and dotted lines overlap.

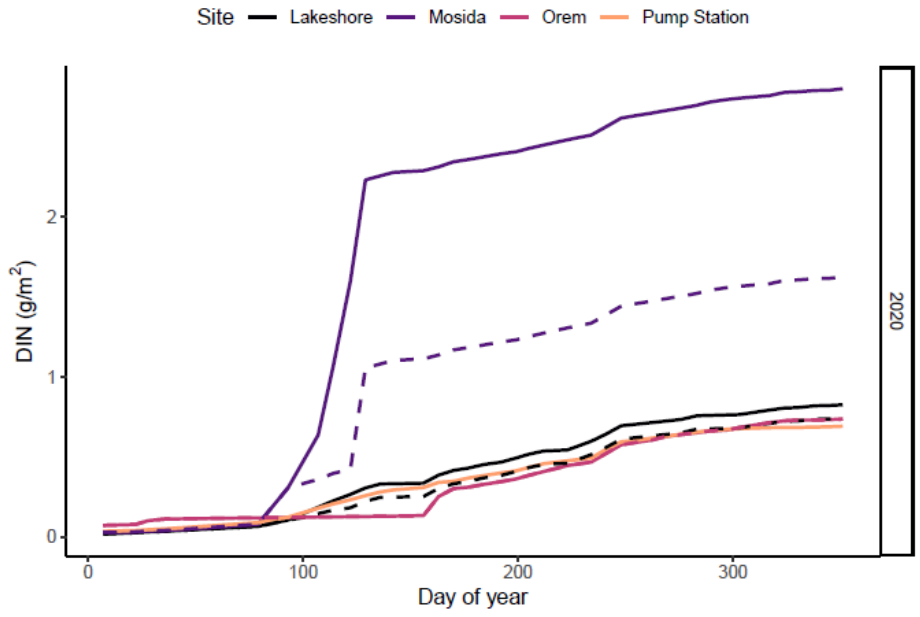

Figure 23. Cumulative DIN flux for the Williams dataset, with gaps in sampling dates imputed by linear interpolation (solid lines) and weather regression (dotted lines). Note that the two imputation approaches were equivalent for Orem and Pump Station, so the solid and dotted lines overlap.

Comparing samples between studies

The W. Miller dataset was not evaluated for outliers and contamination. The sampling design for the W. Miller study also came with several caveats, namely:

Evaporation: The intent for the sampling design was to immediately sample following precipitation events, but this was not always accomplished. If precipitation occurred and was followed by evaporation out of the sampler before the sample was collected, the nutrient flux would be overestimated because the sample would be more concentrated (the flux calculation multiplies the sampled nutrient concentration by the depth of cumulative precipitation over the sampling period, which does not subtract evaporation). Out of 434 samples, 48 had no precipitation except on the sampling day. The potential for evaporation was explored for the situations when precipitation occurred a day or more prior to sampling. The depth of precipitation in each sampler was calculated daily, and daily evaporation rates as measured at the BYU weather station (the only station from the originally identified weather stations with evaporation data) were applied if the precipitation depth was nonzero. If the cumulative precipitation exceeded the depth of the sampler, the precipitation depth was maxed out as the depth of the sampler. On the date of each sampling event, the precipitation depth was reset to zero. Though evaporation sometimes drew down the depth of water in the sampler, sampling events usually occurred close to precipitation events. Therefore, events with substantial evaporation impact were relatively rare (Figure 24).

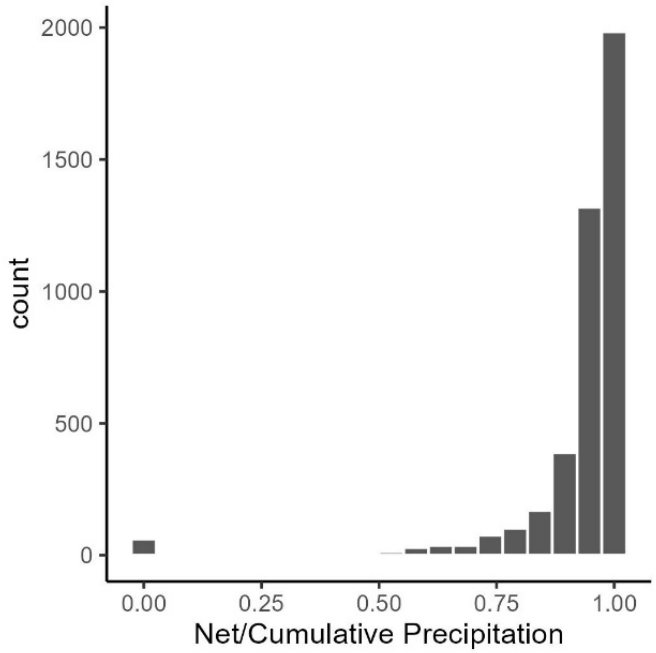

Figure 24. Counts of the ratio of net precipitation (cumulative precipitation minus evaporation) to cumulative precipitation for sampling events in the W. Miller dataset.

Overflow: Given the relative areas of the sampler collector (20 in diameter) and the sampler container (4 in diameter), it was possible that precipitation events of a certain intensity would cause the sampler to overflow. Depending on how evenly atmospheric deposition is distributed across a precipitation event and how homogenized the sample would be inside the container, the potential impact of sampler overflow on the flux could

be overestimation or underestimation. Given the dimensions of the sampler, a precipitation event of >0.48 in would exceed the sampler volume. This magnitude of precipitation was observed in 0.1-3.2% of dates across weather stations and in 48.9-76.7% of sampling events (from cumulative precipitation during the sampling interval) across sampling sites. The latter estimate assumes no evaporation, which would reduce the volume over time.

Loss of Dry Deposition: The sampler was a shallow black pan that funnels into a collection tube. If dry deposition fell onto the collector without falling into the collection tube and was subsequently blown off, the flux would be underestimated. However, it cannot be guaranteed that the collection tubes only contained wet deposition because of the possibility of dry deposition falling into or being washed into the collector.

Sampler Cleaning Between Events: In W. Miller's response to a review by David Gay, he reported that the samplers at BYU, Spanish Fork, and Lehi were cleaned "quite well" between sampling events, whereas the other samplers that were collected by National Weather Service observers were cleaned "now and then." If samplers were not cleaned between each sampling event using a method that would remove nutrients (e.g., acid washing), it is possible that flux estimates would be overestimated due to nutrient residue on the sampler.

Given the lack of availability of data and information to constrain these sources of error, it was determined that the W. Miller dataset would be used as a comparison point to the Williams dataset but would not be prioritized to develop a comprehensive load estimate to the lake.

Decision Point: Interpreting the W. Miller dataset

Subgroup members discussed potential sources of error in the results of the Wood Miller dataset. They primarily focused on four ideas: a) evaporation, b) overflow, c) loss of dry deposition, and d) sampler cleaning between events. Subgroup members had different perspectives on the potential magnitude and impact of each source of error on the Wood Miller study results. They recommended several analyses to evaluate the impact of each potential source of error on the Wood Miller dataset. The analyses provided useful insight into how potential sources of errors impacted the results, but Subgroup members concluded that it did not provide conclusive evidence on the exact degree of impact. Subgroup members concluded that the Wood Miller data is helpful to compare to the Williams dataset to corroborate any high atmospheric deposition values. However, given some of the uncertainties in the Wood Miller data, all Subgroup members recommended using the Williams dataset to calculate the cumulative annual flux and loading to Utah Lake.

TP and fluxes in the W. Miller dataset were significantly lower than in the Williams dataset (ANOVA; $p < 0.01$, $F = 19.6$, $df = 428$) (Figure 25, Figure 26). Similarly, TN fluxes in the W. Miller dataset were significantly lower than the DIN fluxes in the Williams dataset (ANOVA; $p < 0.01$, $F = 18.56$, $df = 424$) (Figure 27, Figure 28). Note that while W. Miller (2021) states that N fluxes were measured as TN, it was verbally confirmed during the Science Panel Subgroup

meetings that the TN measurements were computed as the sum of nitrate and ammonium fluxes, thus representing DIN rather than TN. Thus, the measurements between the two studies are directly comparable. Several sampling sites were common between the two datasets, enabling direct comparison.

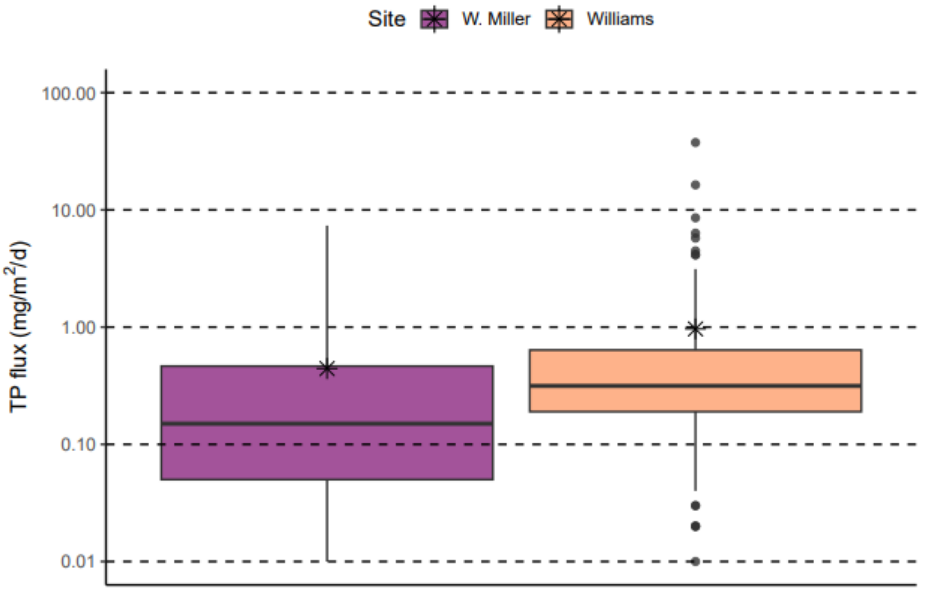

Figure 26. Boxplots of TP flux between the W. Miller and Williams datasets. The star on each plot represents the mean of the data, as opposed to the median which is displayed as the solid horizontal line in the box.

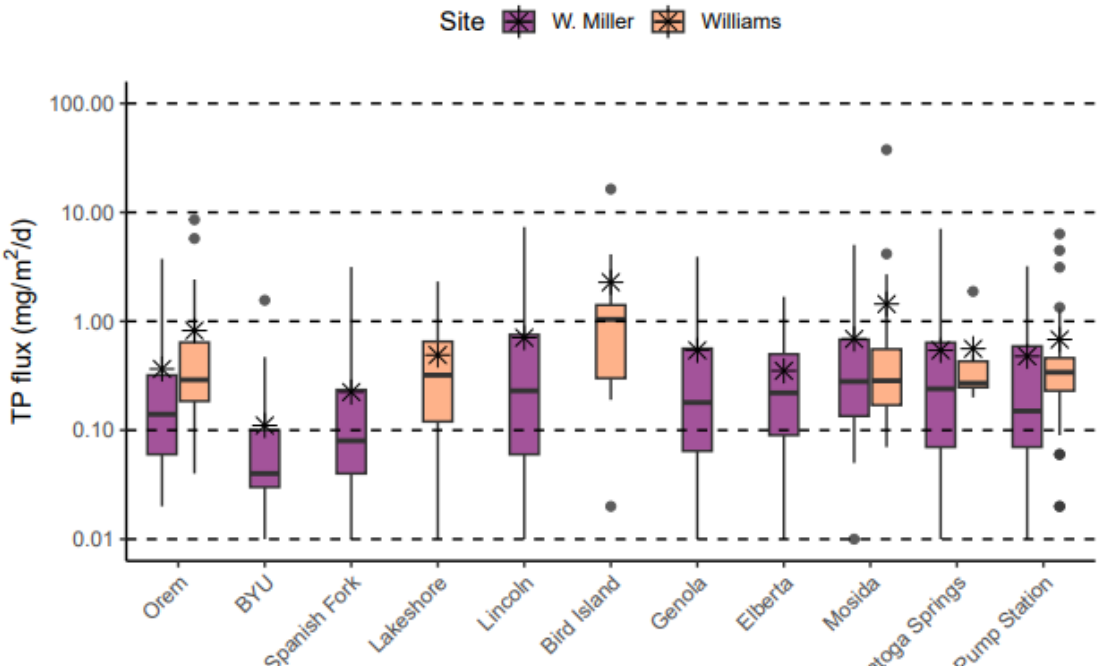

Figure 25. Boxplots of TP flux across sites between the W. Miller and Williams datasets. The star on each plot represents the mean of the data, as opposed to the median which is displayed as the solid horizontal line in the box. Stations are organized in clockwise order across the lake.

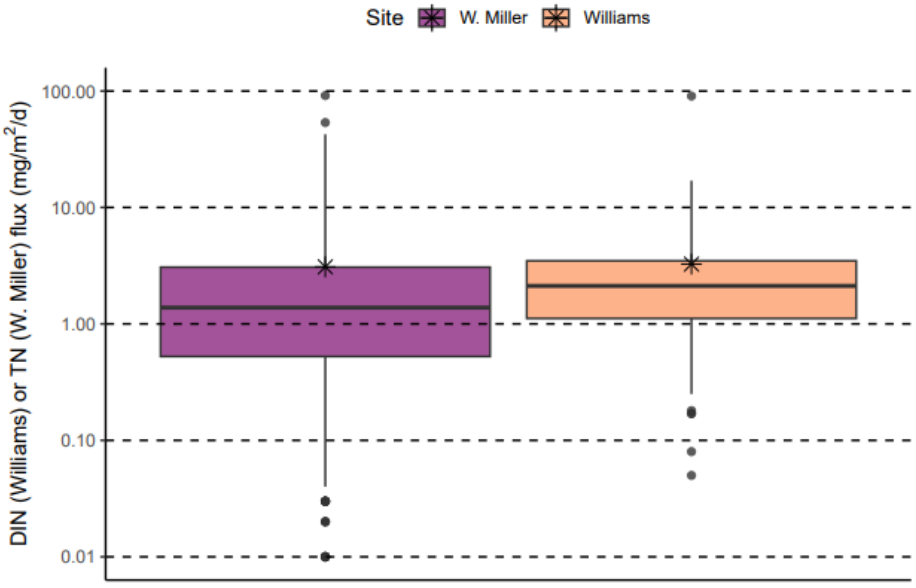

Figure 28. Boxplots of DIN and TN flux between the W. Miller and Williams datasets. The star on each plot represents the mean of the data, as opposed to the median which is displayed as the solid horizontal line in the box.

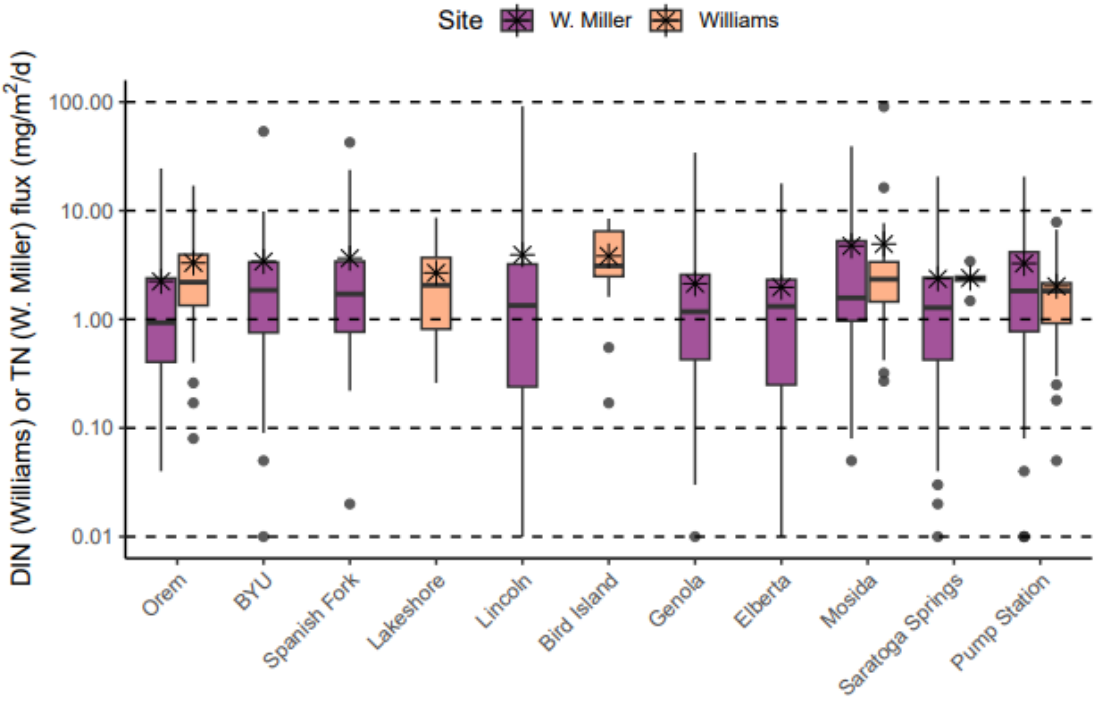

Figure 27. Boxplots of DIN and TN flux across sites between the W. Miller and Williams datasets. The star on each plot represents the mean of the data, as opposed to the median which is displayed as the solid horizontal line in the box. Stations are organized in clockwise order across the lake.

As a result of daily fluxes being generally lower in the W. Miller dataset than the Williams dataset, the calculated cumulative fluxes were also lower (Table 5). Cumulative annual fluxes were available for the W. Miller dataset from 2017-2020, and for the Williams dataset for 2020 only.

Table 5. Cumulative fluxes of nutrients across sites for the W. Miller and Williams datasets.

Dataset	Site	TP Cumulative Flux ($mg/m^2/y$) (min and max)		DIN Cumulative Flux ($mg/m^2/y$) (min and max)	
Williams	Orem	203.5		735.5	
W. Miller	Orem	37.8	101.9	223.1	571.6
W. Miller	BYU	14.4	48.8	479.5	966.2
W. Miller	Spanish Fork	40.1	80.2	467.0	768.7
Williams	Lakeshore	150.0		740.8	
W. Miller	Lincoln	246.5	415.9	571.7	1,852.2
W. Miller	Genola	86.1	504.5	274.0	550.7
W. Miller	Elberta	55.6	129.4	319.6	630.8
Williams	Mosida	444.5		1,624.5	
W. Miller	Mosida	105.8	318.7	495.5	4,385.3
W. Miller	Saratoga Springs	41.0	170.7	365.0	628.3
Williams	Pump Station	235.5		764.2	
W. Miller	Pump Station	80.6	168.6	407.2	650.5

Evaluate spatial interpolation among sites and attenuation of fluxes

Previous studies in other systems demonstrated attenuation of atmospheric deposition fluxes moving away from the source, particularly for locally-derived sources (Wilson and Serre 2007, VanCuren et al. 2012a, 2012b). It follows that for Utah Lake, local sources of atmospheric deposition would be expected to decrease moving away from shore. Regional fluxes may be anticipated to be more equally distributed across the lake. Previous estimates for Utah Lake assumed attenuation of fluxes. Brahney (2019) estimated a first-order decay of fluxes moving away from the shoreline at 200, 400, and 600 m, beyond which was assigned a "background" regional flux. Olsen et al. (2018) assumed "background" fluxes at five interior points in the lake and used kriging to spatially interpolate between the in-lake points and the shoreline sampling sites. Reidhead (2019) assumed a linear fall-off of shoreline fluxes to a point of zero deposition at the center of the lake.

To directly quantify fluxes in the center of the lake and thereby define the magnitude of attenuation, a sampler was installed at Bird Island partway through 2020. Measuring atmospheric deposition at a mid-lake location would allow for the testing of two hypotheses:

> **Hypothesis 1:** Attenuation of atmospheric deposition fluxes occurs as distance increases from land-based local sources. If fluxes are lower at Bird Island than at shoreline sites, this hypothesis would be supported.

Hypothesis 2: Attenuation of atmospheric deposition does not occur, and fluxes at the center of the lake are similar to land-based fluxes. If fluxes are equal in magnitude at Bird Island and shoreline sites and temporal patterns are consistent, this hypothesis would be supported.

However, the daily and cumulative fluxes at Bird Island were higher than other sites (Figure 30 through Figure 33). This observation was not consistent with either hypothesis 1 or 2, thus pointing to other potential hypotheses:

Hypothesis 3: Attenuation of atmospheric deposition does not occur, and there is a land-based source of higher atmospheric deposition that is not captured by the current array of samplers.

Hypothesis 4: The fluxes observed at Bird Island represent a lake-based source of nutrient flux. Possibilities for a lake-based source could include contamination from bird droppings, volatilized material from the island, and spray from lake water.

T. Miller (2022) described support for hypothesis 3, stating "The windrose... shows that Bird Island would be most influenced by shoreline rates from the northwest shore of Utah Lake and the area north of the Mosida sampling site. Neither of these areas have a shoreline sampler. The northwest shore area does not have much agriculture but is experiencing urban expansion in the cities of Lehi and Eagle Mountain. We are exploring the possibility of placing a sampler in this area for future collections." The wind roses around Utah Lake could provide information about the potential prevailing wind patterns moving over the lake (Figure 29). However, wind direction alone cannot fully support the hypothesis of an unsampled high shoreline flux that would explain the magnitudes observed at Bird Island. David Gay, in his review of the report, stated, "One way you might be able to show that this is a real signal goes something like this. The Lakeshore sampling site is not capturing the urban "plume" moving over the lake (plume is to the north). So put another shore line sampler north of Lakeshore where it would capture these high samples." David Gay also provided feedback on the potential for hypothesis 4, either to demonstrate support or rule it out. His review states, "I would expect criticism will come on these observations, such as 'Can you prove that there is no contamination going on in the lake that is not representative of the lake surface?' Condensation into the bucket because the sampler is colder than the water, for example? Mist/droplets from waves being added to the sample? Do the wet only samples also show this difference? Is the difference in the dry side? Bird poop in the dry side? Are the birds using it as a resting place (although then you get into the argument of bird feces as a source)? I would again recommend beefing up the QA [quality assurance] information for the Bird Island sampler. Prove to the reader that you have QA info that shows these samples are valid."

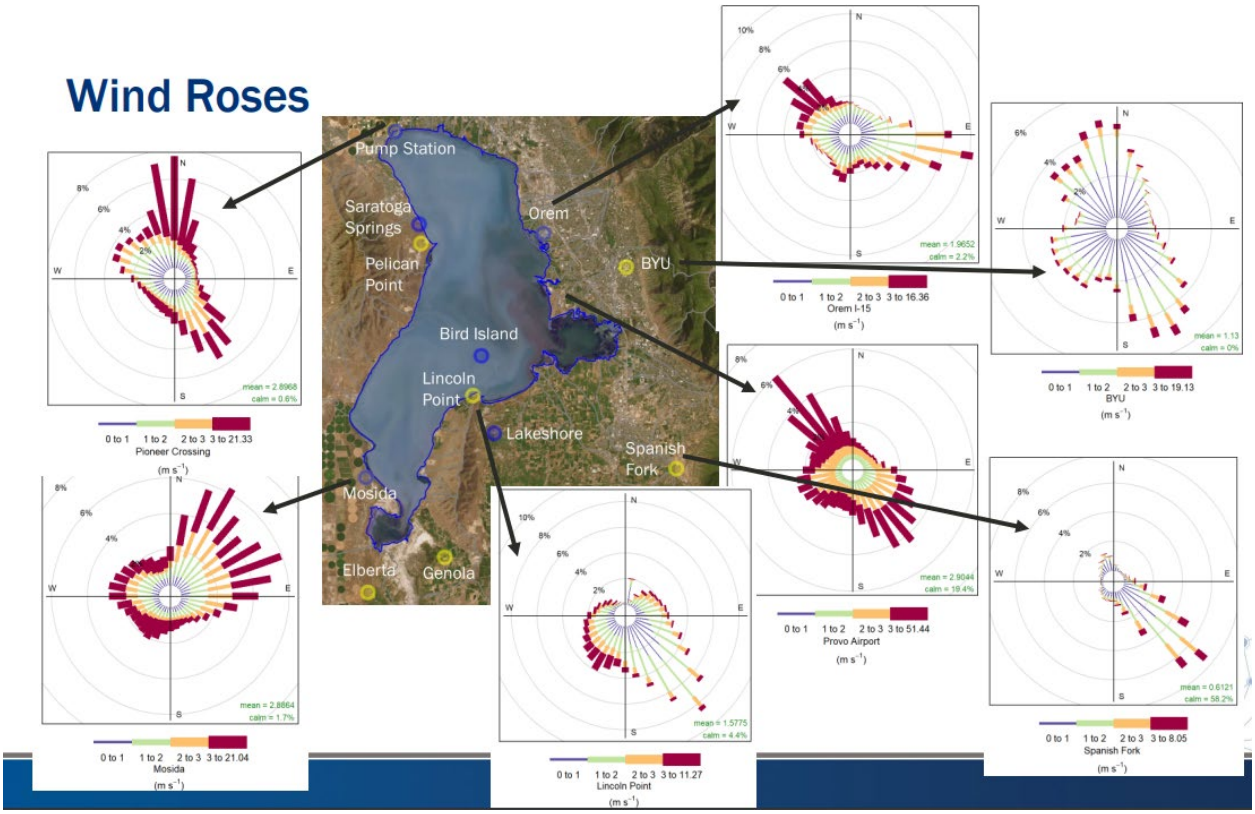

Figure 29. Wind rose data for seven weather stations located around Utah Lake.

Decision Point: Bird Island Data

Subgroup members discussed whether, and if so, how data collected from samplers on Bird Island could inform the atmospheric deposition loading analysis. The Subgroup members did not reach a consensus on their recommendation on whether to incorporate Bird Island data into the atmospheric deposition analysis.

The majority of the Subgroup members supported retaining the Bird Island data as a representation of point source nutrient input but not using it to estimate external atmospheric deposition influx into Utah Lake. The Subgroup members who supported this decision stated that they were concerned that birds could have deposited droppings into the samplers due to the number of birds visiting the Island. These droppings would increase the N and P values in the sampler. They acknowledged that bird droppings are a nutrient source to Utah Lake but that the fluxes calculated at Bird Island may not be representative of atmospheric deposition inputs across all of Utah Lake since the sampler is stationed at a bird rookery. Furthermore, since birds may be eating organisms from Utah Lake, their droppings may not necessarily represent a net influx of nutrients to Utah Lake. Additionally, Subgroup members expressed concerns about other potential influences on the samplers, including the aerosolization of bird materials from the island and spray from the lake water.

One Subgroup member did not support this decision. They stated that the Bird Island samplers should be used to estimate the annual atmospheric deposition nutrient load to Utah Lake and that the data from the Bird Island sampler indicates that atmospheric deposition is not attenuating across Utah lake. They also stated that the samplers did not show evidence that bird droppings got into the samples. They shared that perching birds do not travel to Bird Island due to its distance from the shore, and the webbed-footed birds that travel to the Island would be unable to perch on the sampler. Additionally, they collected samples of bird droppings around Utah Lake. They measured that the nutrient content of those droppings was five to ten times higher than the nutrient concentration values found in the Bird Island sampler, suggesting that bird droppings did not influence the data collected at Bird Island. Other Subgroup members stated that this evidence is inconclusive in determining whether bird droppings influence Bird Island sampler data, as droppings could have partially been deposited into a sampler.

As an alternative explanation for why atmospheric deposition flux values were higher at Bird Island than at the shoreline samplers, the Subgroup member in the minority hypothesized that the southeastern winds and eastern winds from the canyons could transport and deposit dust and aerosols to the Bird Island sampler in the evening and early morning. Southwestern prevailing winds could transport and deposit dust and aerosol particles to the Bird Island sampler in the afternoon. The southeastern and southwestern winds would converge over Utah Lake and settle dust and aerosols near the Bird Island sampler, which is why the values from the Bird Island sampler are higher than the shoreline samplers. Additionally, they stated that there is an inversion nearly every day over Utah Lake, which results in the deposition of aerosols from urban zones into Utah Lake, including the area near the Bird Island sampler.

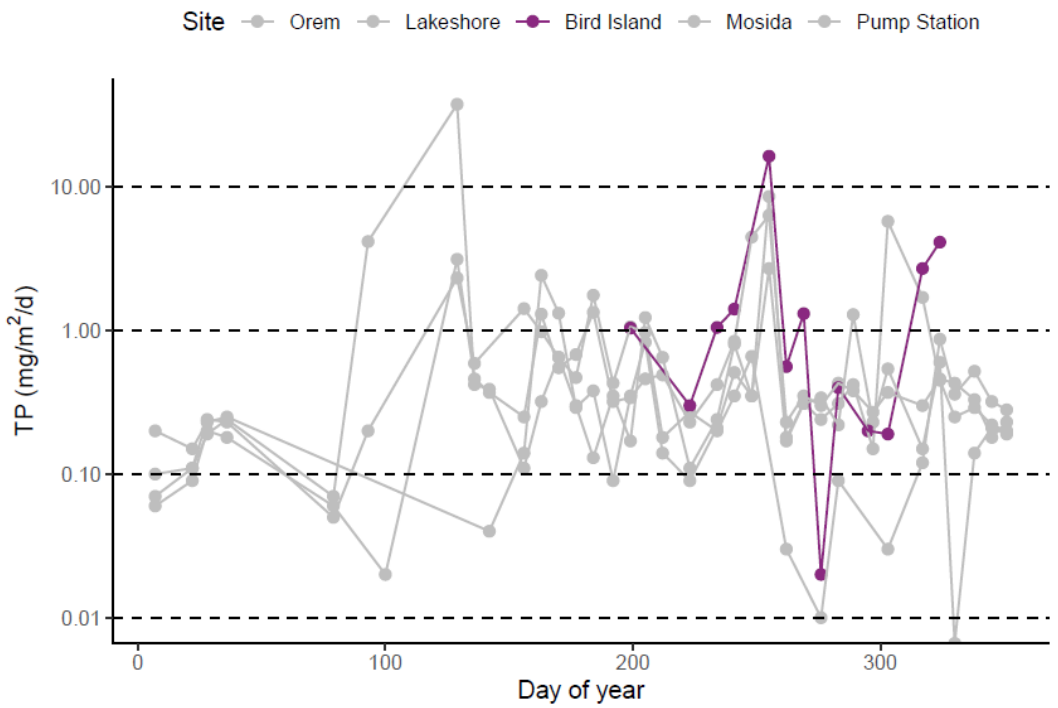

Figure 30. Time series of TP fluxes in the Williams dataset, with Bird Island fluxes highlighted (purple) compared to other sites (gray).

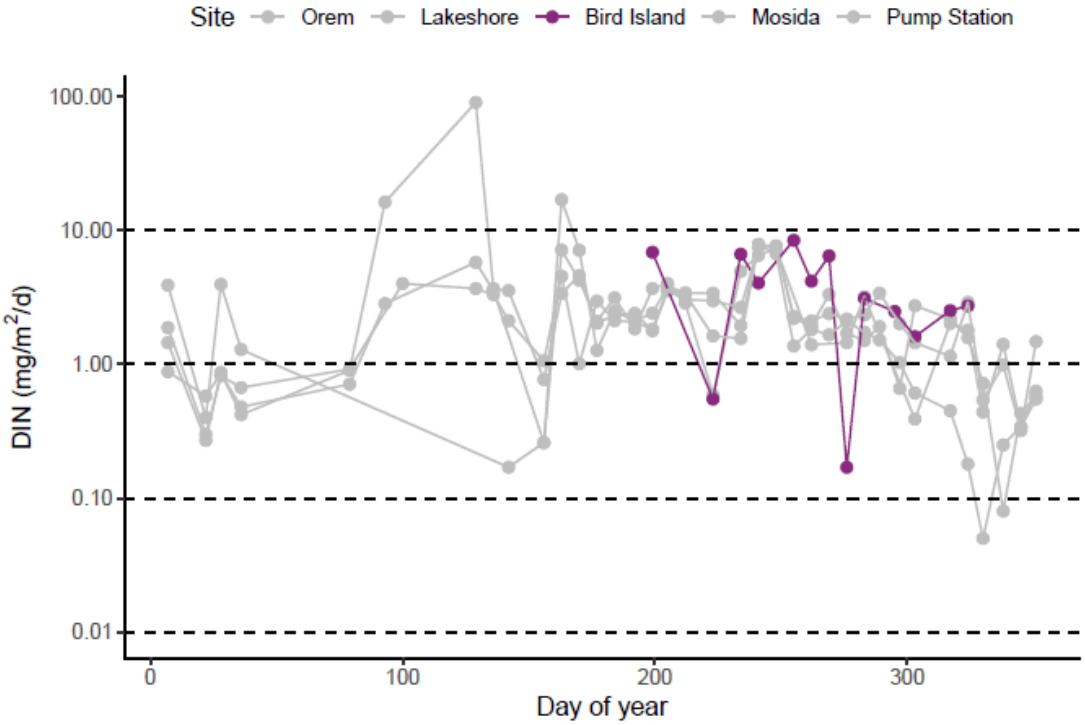

Figure 31. Time series of DIN fluxes in the Williams dataset, with Bird Island fluxes highlighted (purple) compared to other sites (gray).

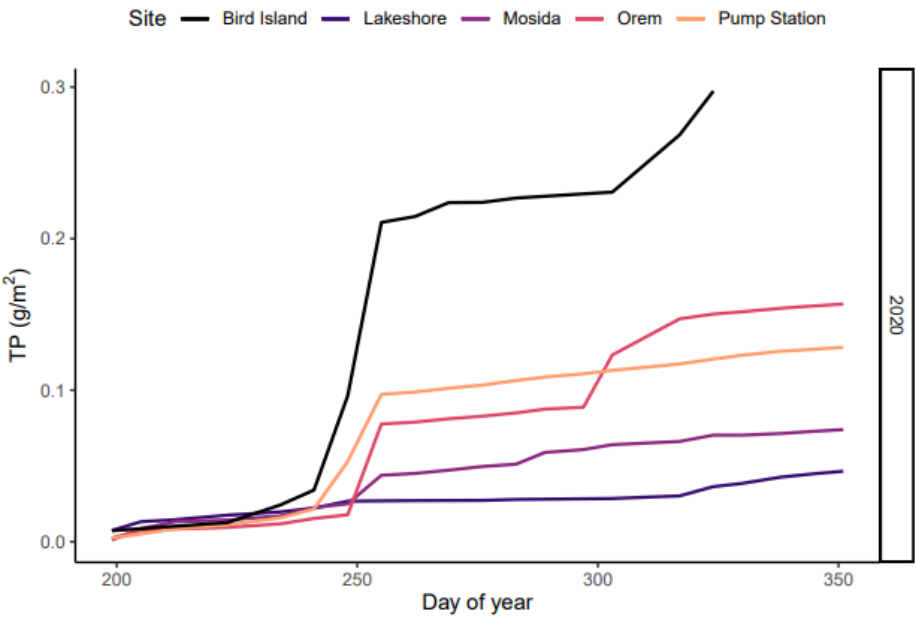

Figure 32. Cumulative TP fluxes for the Williams dataset, starting on the date when the Bird Island sampler was installed.

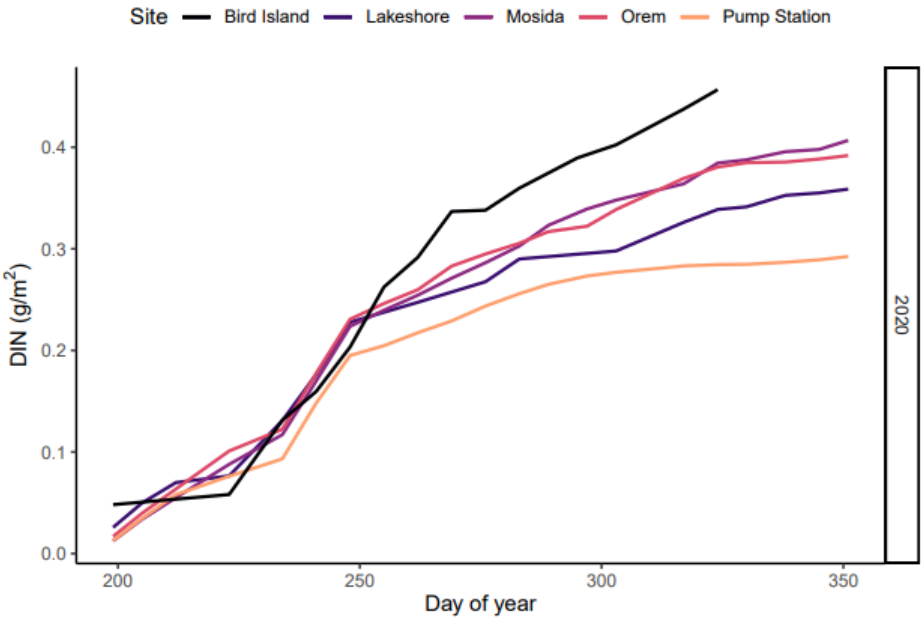

Figure 33. Cumulative DIN fluxes for the Williams dataset, starting on the date when the Bird Island sampler was installed.

In the absence of using Bird Island to characterize the degree of attenuation of atmospheric deposition, observations from the literature were explored. Jassby et al. (1994) measured nutrient fluxes in atmospheric deposition across Lake Tahoe, noting that dry deposition of DIN increased moving toward mid-lake (potentially due to canopy uptake of DIN in forested sites) and dry deposition of SRP decreased moving toward mid-lake. Wet deposition decreased moving toward mid-lake for both DIN and SRP, likely due to precipitation patterns in the basin. Wet deposition made up the majority of nutrient deposition, suggesting that in total, atmospheric deposition decreased moving toward mid-lake. The drivers of atmospheric deposition in the forested, snowpack-dominated Lake Tahoe basin may be expected to be different than the drivers in Utah Lake.

In a later study in Lake Tahoe, VanCuren et al. (2012a and 2012b) observed aerosol size and concentrations. The findings from these two related studies highlighted that regional sources of dry deposition tended to be fairly steady across the lake, whereas local sources such as urban areas tended to be highly localized, with fluxes dropping off moving away from shore. While all particles followed an exponential decay rate moving away from local sources, larger particles tended to attenuate more rapidly than smaller particles.

A non-lake example that may still shed light on attenuation of local sources of atmospheric deposition was a study conducted in terrestrial systems located near concentrated animal feeding operations (CAFOs) in North Carolina (Wilson and Serre 2007). This study focused specifically on ammonium and noted that ammonium concentrations decreased with distance from CAFOs. The steepest decrease in ammonium concentrations was between the 0.0-0.5 km to 0.5-1.0 km distance bins. A dominance of regional sources was noted beyond distances of 2 km.

Goodman et al. (2019) sampled bulk dust grain sizes in the region surrounding Utah Lake. Grain sizes were similar between fine playa, snow, and urban dust. The most common grain sizes were 10 µm for playa dust and 20 µm for urban and snow dust. It is acknowledged that fine playa dust is distributed more widely than might be anticipated given the grain size, given the widespread observation of playa dust across samplers in the region. The grain size of other types of dust particles, however, may shed light into the potential attenuation rates for these local sources of dust. If grain sizes from Goodman et al. (2019) are applied to the observations from VanCuren et al. (2012a), attenuation would be anticipated to be rapid moving away from the source, with an exponential decay rate and a range of ~100 m.

Decision Point: Attenuation of Fluxes

Subgroup members discussed whether, and if so, how to apply attenuation rates to the calculation of atmospheric deposition loading to Utah lake. After reviewing and discussing the Jassby et al. (1994), VanCuren et al. (2012a and 2012b), Goodman et al. (2019), Carling (2022), and Wilson and Serre (2017) papers, Subgroup members agreed that dust and aerosols attenuate as a function of distance. They did not agree on the attenuation distance or rate for shoreline samplers at Utah Lake.

Subgroup members discussed that factors like wind speed, particle size, and particle shape affect attenuation. They talked about several different methods to identify an attenuation rate.

· Use standard attenuation rates based on NADP models: One suggestion was to use a standard attenuation rate based on National Atmospheric Deposition Program (NADP) models. One challenge with this approach is that the NADP models only have a standard attenuation rate for wet deposition and do not have a standard attenuation rate for dry deposition. Since most of the samples collected on Utah Lake were bulk samples, the attenuation rates from the NADP models cannot be applied to the Utah Lake samples.

· Use the Goodman et al. (2022) grain size and the VanCuren (2012a) attenuation rates by grain size: This methodology would involve cross-analyzing the Goodman et al. (2022) grain size with VanCuren (2012a) attenuation rates by grain size to establish an attenuation rate. One advantage of this methodology is it uses grain size information from areas around Utah Lake. One disadvantage of this methodology is it assumes grain size is equivalent to N and P fluxes. The potential attenuation distance based on this methodology is 100 meters.

· Use the attenuation rate identified by Wilson and Serre (2007) paper: The Wilson and Serre (2007) paper measured the attenuation rates of local sources. The study's focus on the attenuation rate of local sources is a particular advantage of this study. One disadvantage of this study is that it only analyzed ammonia and no other constituents, so applying the study's attenuation rate to the Utah Lake atmospheric deposition data would assume that all constituents attenuate at the same rate as ammonia in this study. This study also focuses on ammonia from hog farms, which is not the specific local source around Utah Lake. The potential attenuation distance based on the results of this study is two kilometers.

The majority of Subgroup members supported applying an attenuation rate to the shoreline fluxes based on the Goodman et al. (2022) grain size and the VanCuren (2012a) attenuation rates by grain size (potential attenuation rate of 100 meters).

One Subgroup member did not support the decision to apply an attenuation rate to the shoreline fluxes based on the Goodman et al. (2022) grain size and the VanCuren (2012b) attenuation rates by grain size. Their perspective was that the shoreline fluxes do not attenuate to the center of Utah Lake. They cited the data from Bird Island as evidence that wind patterns can deposit fine particles far into Utah Lake, suggesting that attenuation is not occurring across Utah Lake.

All Subgroup members agreed to have Tetra Tech calculate multiple atmospheric loading estimates using different attenuation rates. They planned to use different loading estimates to select a primary loading value to calibrate the Utah Lake in-lake model and a low and high loading value to be used in a sensitivity analysis.

Based on the observations in the literature, several attenuation scenarios were considered, whereby local sources were anticipated to decrease moving away from shore. Three scenarios were defined, representing attenuation distances of 100 m (observed in VanCuren et al. 2012a), 200 m (VanCuren et al. 2012a plus a buffer distance to account for uncertainty), and 2000 m (observed in Wilson and Serre 2007) (Figure 34, Table 6). The exponential decay pattern observed in VanCuren et al. 2012a for particles 10-25 µm was used, consistent with local deposition in the basin that had average grain sizes of 20 µm (Goodman et al. 2019). Because the atmospheric deposition samplers did not distinguish between types of sources, the bulk atmospheric deposition values in the Williams dataset presumably contain both local and regional sources of atmospheric deposition. Therefore, fluxes with both local and regional influence would be expected close to shore (i.e., fluxes from Williams samplers), and those loads would attenuate to a regional-only source moving away from the shoreline.

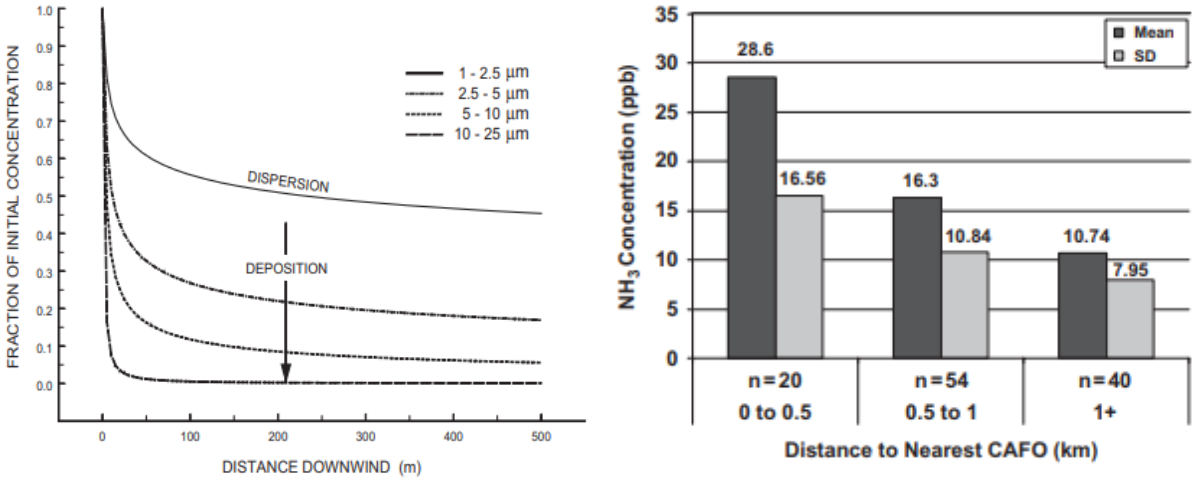

Figure 34. Illustration of attenuation from VanCuren et al. 2012a (relevant particle size: 10-25 µm) and Wilson and Serre 2007. Reproduced from Figure 11 and Figure 3 of the respective references.

Table 6. Attenuation scenarios based on information in VanCuren et al. 2012a and Wilson and Serre 2007.

Shoreline flux proportion	Regional flux proportion	100 m scenario	200 m scenario	2000 m scenario
1.00	0.00	0 m	0 m	0 m
0.30	0.70	20 m	40 m	400 m
0.045	0.955	50 m	100 m	1000 m
0.026	0.974	100 m	200 m	2000 m

In order to apply the attenuation scenarios in Table 6, estimating a regional flux was necessary. To estimate regional fluxes of TP, data from Goodman et al. (2019) and Carling (2022) were used. Urban dust fluxes in municipalities around Utah Lake had an average of 30.5 g/m^2/yr (range: 24.7-34.9 g/m^2/yr). 91% of urban dust was estimated to be regional in nature, leading to a regional dust flux estimate of 27.8 g/m^2/yr. Putman et al. 2022 also collected bulk dust deposition, this time near Lehi, and obtained regional dust deposition estimates of 14.6-36.6 g/m^2/yr, representing a good groundtruthing of the estimates derived from Goodman et al. (2019). According to Carling (2022), P content in regional dust was 1,344-4,340 mg/kg. Converting regional dust mass to a mass of TP leads to an average of 79 mg TP/m^2/yr (range: 37.4-120.7 mg TP/m^2/yr). The annual TP regional flux is higher than Brahney (2019) due to a lower estimate of regional dust deposition derived from mountain regions sourced east of the Colorado Plateau in the Brahney (2019) estimate.

*Regional TP flux = (Bulk flux * Proportion regional in bulk) * Regional TP content*
*79 mg TP/m^2/yr = 30.5 g/m^2/yr * 0.91 * 2,842 mg/kg*

To estimate regional sources of DIN, values form Brahney (2019) were used, which were derived from the CMAQ model (which includes data from CASTNET, NADP, AirMoN, and NADP NTN). The DIN deposition estimate derived from CMAQ was 575 mg DIN/m^2/yr (range: 400-750).

Decision Point: Estimate of regional fluxes

Subgroup members supported calculating a regional flux to be applied across the entire surface of Utah Lake. This decision means that the shoreline fluxes will attenuate to a baseline regional flux instead of to zero.

The rationale for this decision was that the evidence from Carling (2022) and Goodman et al. (2019) suggested playa dust contributes to a regional flux that would not attenuate over Utah Lake. The Subgroup members supported using the data from Carling (2022) and Goodman et al. (2019) to identify a regional flux for TP to Utah Lake. The average value of the TP flux calculated from the Carling (2022) and Goodman et al. (2019) data was used as the regional bulk sample and applied across Utah Lake. Subgroup members supported using the CMAQ modeling from Brahney (2019), which included data from CSTNET, NADP, AirMoN, and NADP NTN, to estimate the regional flux of DIN to Utah Lake.

After calculating the regional flux of DIN, one Subgroup member noted that the estimate (440-750 mg DIN/m2/year) fits within the N flux range calculated using the Williams dataset. This Subgroup member stated that he did not understand why the N flux range calculated from the Williams dataset is acceptable, but the calculated P flux range from the same studies is not.

Determine loading to Utah Lake for including in the ULNM

Methods

To calculate the loads of TP and DIN to Utah Lake, rates of cumulative annual fluxes from the Williams dataset were combined with attenuation scenarios and regional flux estimates. Total load to Utah Lake was calculated in several steps:

1. ***Create a raster layer of shoreline fluxes around the edge of Utah Lake.*** Four shoreline sampling sites from the Williams dataset were used (Orem, Lakeshore, Mosida, and Pump Station). Spatial interpolation via inverse distance weighted interpolation generated flux estimates for all locations around Utah Lake (Figure 35)

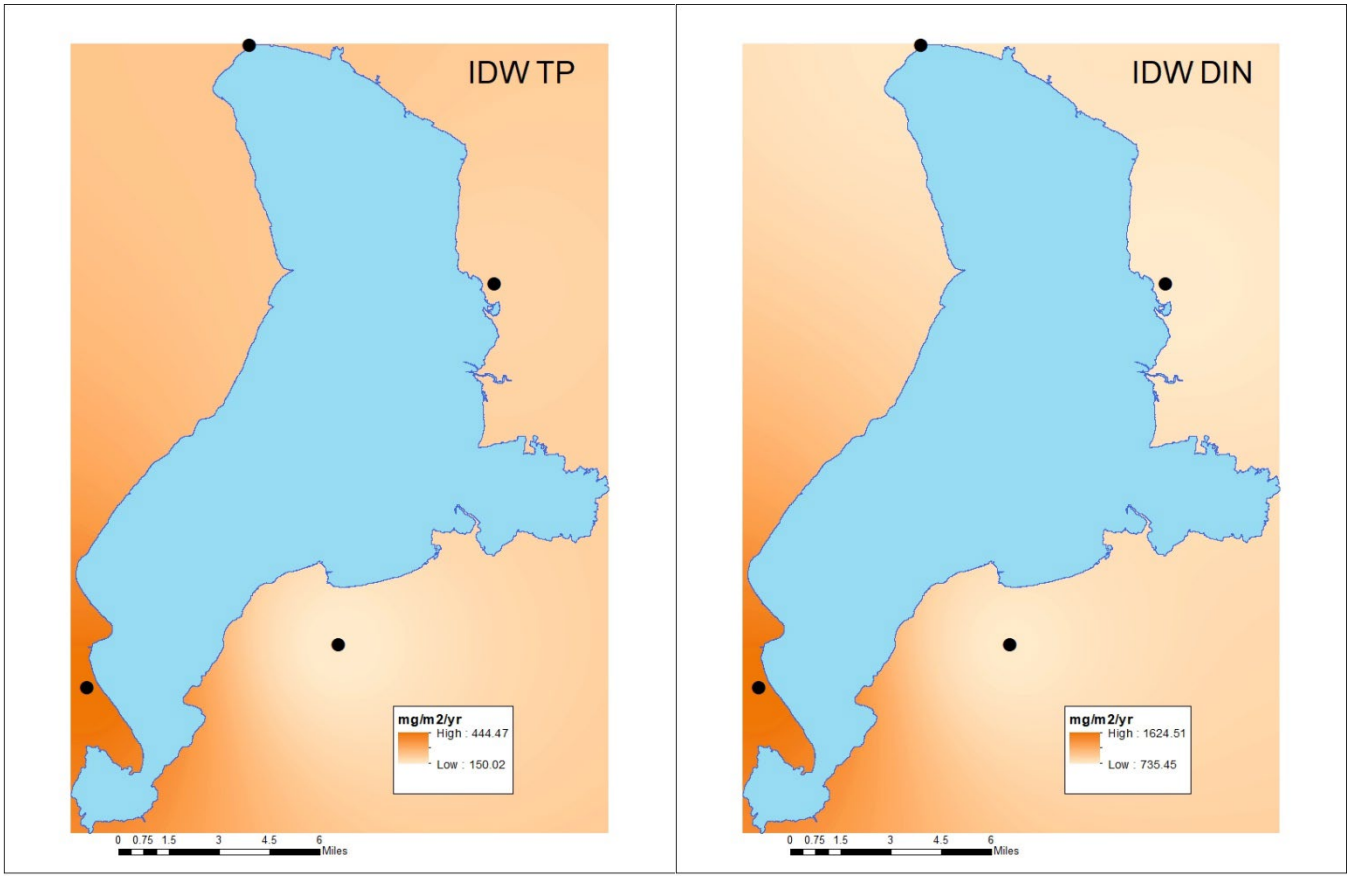

Figure 35. Inverse distance weighted (IDW) spatial interpolation of shoreline fluxes of TP (left) and DIN (right) based on observations at the four sampling sites in the Williams dataset for 2020. Sampling sites (clockwise starting on the east side of the lake) were Orem, Lakeshore, Mosida, and Pump Station.

2. ***Assign the decay rate of shoreline fluxes moving from shoreline to offshore in Utah Lake.*** See Table 6 for details of the three scenarios (Figure 35).
3. ***Assign the regional flux in areas of Utah Lake that are beyond the shoreline decay distance.*** Fluxes of 79.0 mg TP/m^2/yr and 575 mg DIN/m^2/yr were applied as estimates of regional flux (Figure 36).

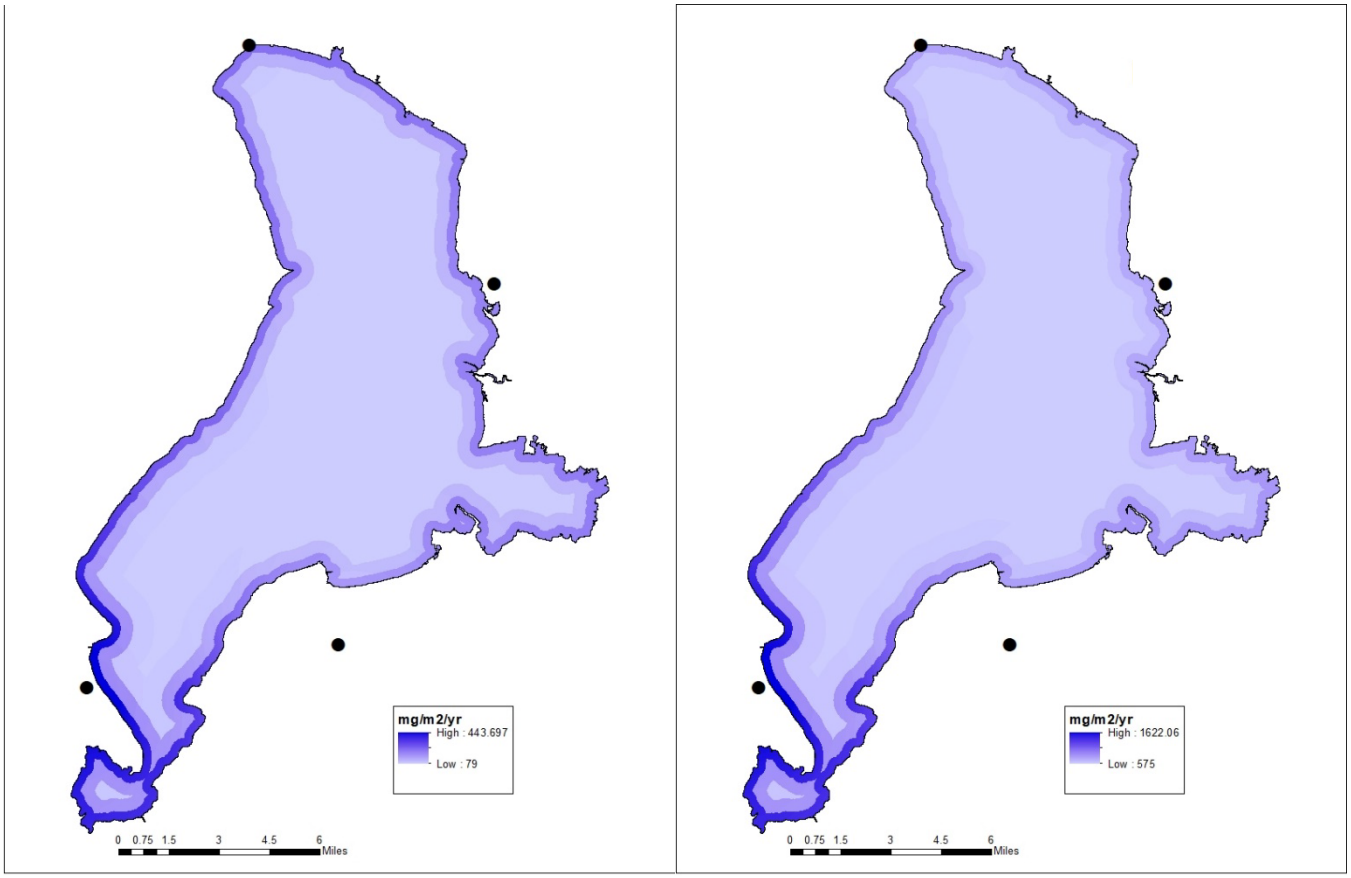

Figure 36. Display of the estimate of TP (left) and DIN (right) loading to Utah Lake, which incorporates shoreline fluxes (local and regional atmospheric deposition sources) at the edge of the lake that attenuate to a regional flux moving toward the middle of the lake. The width of each band represents the distances assigned based on the attenuation scenario (the 2000 m scenario is displayed as an example). Note that areas of higher shoreline flux, namely in the southwest portion of the lake, have higher nearshore fluxes than areas with lower shoreline flux.

In addition, a fourth scenario was run, which assumed no attenuation but simply applied the inverse distance-weighted interpolation of shoreline fluxes across the lake (Figure 37). This scenario represented a maximum possible load (i.e., assuming no attenuation) based on available information.

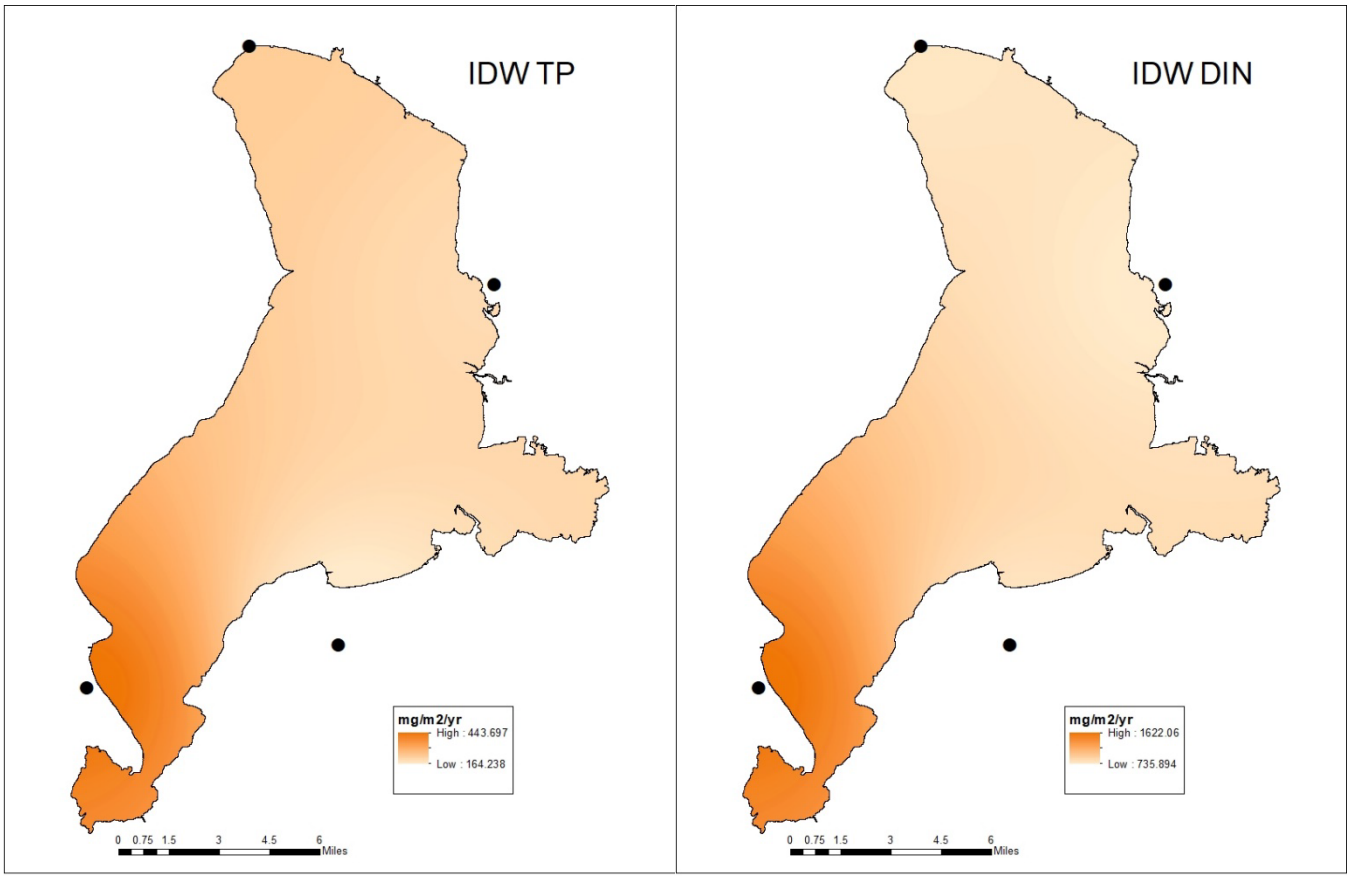

Figure 37. Inverse distance weighted (IDW) spatial interpolation of shoreline fluxes of TP (left) and DIN (right) across the lake, thus representing a "no attenuation" scenario. The flux values are based on observations at the four sampling sites in the Williams dataset for 2020. Sampling sites (clockwise starting on the east side of the lake) were Orem, Lakeshore, Mosida, and Pump Station.

Results

The attenuation scenarios resulted in total load estimates to Utah Lake of 31-45 metric tons TP/yr and 218-249 metric tons DIN/yr (Table 7). The scenario assuming no attenuation resulted in total load estimates of 93 metric tons TP/yr and 351 metric tons DIN/yr. These scenarios fell in the range of other constraining analyses and were lower than previous published estimates that included contaminated samples.

Table 7. Atmospheric deposition loading estimates for Utah Lake as a result of this analysis (rows 1-4 in blue) compared to constraining analyses (rows 5-9 in white) and other published studies (rows 10-12 in blue).

Scenario	**TP** (metric tons/yr)	**DIN** (metric tons/yr)	**Notes**
100 m attenuation	31	218	
200 m attenuation	32	220	
2000 m attenuation	45	249	
No attenuation	93	351	
Carling 2022	57.5		Dust conversion, assumes no attenuation.
Brahney 2019	2-21	153-288	Assumes attenuation of local sources and no attenuation of regional sources at 200, 400, and 600 m distance.
Brahney	33		Mass balance
Brett	60	257-409	Mass balance
W. Miller 2021	50-104	57-570	Assumes no attenuation Loads reported by W. Miller, not calculated in this report.
Olsen et al. 2018	10-430	637	Low loads include uncontaminated samples only, and high loads include contaminated samples. Included attenuation by assigning background fluxes the lake interior and interpolating via kriging.
Reidhead 2019	193	482-1,052	Unscreened samplers, could include contamination. Included attenuation by assigning a linear fall-off of deposition to a point of zero at the lake center.
Barrus et al. 2021	133-262		Low loads represent partially screened 2020 samples, and high loads represent unscreened 2019 samples with some contamination. Assumes no attenuation by incorporating fluxes at Bird Island.

Decision Point: Loading recommendations

Subgroup members evaluated atmospheric loading estimates for TP and DIN based on four attenuation scenarios:

• Shoreline fluxes attenuate at 100 meters off the shoreline (based on the VanCuren (2012a) attenuation rate by grain size and Goodman et al. (2019) grain size data)
• Shoreline fluxes attenuate at 200 meters off the shoreline (based on VanCuren (2012a) attenuation rate by grain size and Goodman et al. (2019) grain size data plus a buffer to account for uncertainty)
• Shoreline fluxes attenuate at 2,000 meters off the shoreline (based on Wilson and Serre (2007)
• Shoreline fluxes do not attenuate across Utah Lake

All attenuation scenarios included a regional flux of 79.0 TP mg/m_2/yr based on Carling (2022) and Goodman et al. (2019) and 575 DIN mg/m_2/yr based on CMAQ modeling from Brahney (2019), meaning the shoreline fluxes attenuated to the regional flux value rather than zero.

The Utah Lake modeling team requested that the Subgroup provide a primary recommendation to calibrate the model and a low and high recommendation for a sensitivity analysis once the model is calibrated.

The majority of Subgroup members supported using the atmospheric deposition loading values based on the 200-meter attenuation rate as the primary recommendation for model calibration (TP: 32 metric tons/year; DIN: 220 metric tons/year). They also supported using the atmospheric deposition loading values based on the 100-meter attenuation rate as the low recommendation (TP: 31 metric tons/year; DIN: 218 metric tons/year) and the 2,000-meter attenuation rate as the high recommendation (TP: 45 metric tons/year; DIN: 249 metric tons/year) for the sensitivity analysis. They stated that the VanCuren (2012a) attenuation rates by grain size and the Goodman et al. (2019) grain size data suggest that local sources attenuate across Utah Lake.

One Subgroup member did not support the recommendation for atmospheric deposition loading values. They recommended that the primary TP loading recommendation for model calibration is 150 metric tons/year, the low TP loading recommendation is 93 metric tons/year (the Subgroup analysis value that assumes no attenuation), and the high TP loading recommendation is 200 metric tons/year. These values are based on calculations of the Williams dataset in its entirety (i.e., no samples removed). Additionally, they cited the Bird Island data as evidence that suggests no attenuation of local sources occurs across Utah Lake. Accordingly, their low recommendation is based on this conclusion from the Bird Island dataset. The detailed reasoning for their TP and DIN loading value recommendations is forthcoming.

Evaluate chemical speciation

The proportions of N constituents compared to DIN, on average across sites, were 30.25% for nitrate and 69.75% for ammonium (Table 8). The proportion of SRP compared to TP was 37.5%, on average across sites. Proportions of N constituents tended to be fairly consistent across sites except Mosida, suggesting a possible local influence that has a higher proportional abundance of ammonium relative to nitrate. Proportions of SRP relative to TP ranged from 24-46% across sites and was more consistent with regional dust proportions than urban dust proportions (Brahney 2019).

Table 8. Proportions of chemical constituents in DIN and TP across sites and compared to other studies.

Study	Site	Nitrate/DIN	Ammonium/DIN	SRP/TP
Williams data 2020	Orem	0.35	0.65	0.46
	Lakeshore	0.37	0.63	0.48
	Mosida	0.10	0.90	0.24
	Pump Station	0.39	0.61	0.27
Brahney 2019	Urban dust			0.75
	Regional dust			0.34
Reidhead 2019	Utah Lake shoreline sites			0.37
W. Miller 2021	Utah Lake shoreline sites			0.32

The Utah Lake Nutrient Model specifies specific constituents needed as inputs for atmospheric deposition. These constituents are organic N, nitrate, and ammonium for N, and orthophosphate and organic P for P. Apportioning the DIN load as 30.25% nitrate and 69.75% ammonium, with an unknown amount apportioned to organic N was determined as the recommendation for N. Apportioning the P load was a more complicated recommendation to derive, as much of the TP load to Utah Lake could be expected to be sediment-bound P that is neither organic nor orthophosphate. The recommendation was to assign 37.5% of the TP load as orthophosphate and to allow the modeling team to determine the best course of action to characterize the reactivity and chemical behavior of the remainder of the TP load. The temporal and spatial distribution of the load was also recommended to be determined by the modeling team.

Decision Point: Chemical speciation

The Utah Lake modeling team requested that the Subgroup provide organic N, nitrate, and ammonium as the N constituents. All Subgroup members supported apportioning the N load as an unknown proportion organic, 30.25% of DIN as nitrate, and 69.75% DIN as ammonium based on the proportions of chemical constituents measured in the Williams dataset.

Additionally, the Utah Lake modeling team requested that the Subgroup provide orthophosphate and organic P as the P constituents to input into the model. One challenge with apportioning P in the model is that the datasets available to the Subgroup contained information on orthophosphate but did not contain information on organic P. Subgroup members discussed how to apportion P, given the limitations in the data.

One suggestion from a Subgroup member was to determine the fraction of TP that is calcium-bound. Assuming that calcium-bound P is not bioavailable, the modeling team could subtract the fraction of calcium-bound P from TP, generating a value of bioavailable phosphorous for primary production. There is data on the amount of calcium-bound P in the Utah Lake sediment, but this evidence is not representative of the amount of calcium-bound P coming from atmospheric deposition since the calcium-bound P in the sediment comes from multiple sources (e.g., rivers, in-lake precipitation, etc.). Additionally, Subgroup members noted that magnesium and iron-bound P could contribute bioavailable P to Utah Lake if these bounded particles encounter anoxic conditions at the Utah Lake sediment-water interface. Subgroup members noted studies that may contain information on P speciation of the fine playa dust (i.e., the regional dust) and be useful in apportioning total P, including Brahney (2019), Dr. Josh LeMonte's forthcoming study on P-binding, and Goodman et al. (2019).

Given the limitations in the available data, Subgroup members supported having the Tetra Tech modeling team develop an approach to characterize P speciation in the model for review.

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APPENDIX

AD Subgroup Analysis Plan

Objectives

4. Analyze available information and data to improve understanding of atmospheric deposition to Utah Lake
5. Work collaboratively toward a recommendation for atmospheric loading, ideally achieved through consensus
6. Document the SP's decision-making process for analyzing and evaluating evidence and working toward an atmospheric deposition recommendation

Tasks

1. **Review and summarize raw data from G. Williams (Olsen 2018, Reidhead 2019, and Barrus 2021) and W. Miller datasets (SP with Tt support)**

   Purpose and goals

   - Process directly sampled data using transparent and reproducible methodology
   - Evaluate data QA/QC and distributions
   - Compare spatial and temporal variability across sampling sites

   Data needs

   - Raw data from Olsen, Reidhead, and Barrus (partially acquired, verify that information on wet/dry samplers, paired sampler height experiment, and screened/unscreened sampler experiment data are available and designated)
   - Raw data from W. Miller (acquired)
   - Surface area of W. Miller sampler (for converting concentration and volume to areal flux)
   - Raw 2021 data

   Analysis

   a. Data processing
      i. Impute nondetects
      ii. For each site and sampling date, convert raw data to areal flux
      iii. Flag outliers
   b. Data exploration
      i. Description of sampling locations, sample size, and period of record for each dataset and site
      ii. Summary statistics for each site
      iii. Summarize location, date, and constituent for flagged outliers
   c. Visualization
      i. Boxplots of flux at each site
      ii. Time series plots of flux at each site
      iii. Cumulative flux plots at each site

   Output (see details in Analysis section above)

   - Summary of data processing steps

- Summary statistics
- Visualizations
- Outlier tables

Decision points

- How to impute nondetects
- How to deal with missing data (interpolation, etc.)
- How to identify outliers

2. Evaluate outlier samples for potential explanations (i.e., collection methodology including table height and screens; sources of contamination including insects, leaves, algae; influence of local weather; and potential localized sources) (SP with Tt support)

2.1. Review and discuss previous Science Panel and third-party recommendations for atmospheric deposition (SP with Tt support)

Purpose and goals

- Identify and review existing and relevant SP and David Gay recommendations to inform the forthcoming analytical approach

Data needs

- Previously developed SP recommendations and summaries (acquired)
- David Gay review of reports and products (acquired)

Topics

- Sampler screening
- Sampler data QA/QC
- Excluding insects and other materials (e.g., algae, leaves) as sources of atmospheric deposition
- Sampler height
- Wet/dry vs. bulk sampler design
- David Gay document review
- Attenuation
- Nutrient speciation
- Consideration of multiple lines of evidence: direct sampling, local & regional dust modeling, mass balance, sediment accumulation, global reviews

Output

- Summaries of SP decisions/recommendations/discussions to date for each topic
- A list of specific topics for further investigation and proposed analytical approaches for each.

Decision points

- SP recommendations for proceeding with data analysis, analytical approach, and weighing lines of evidence. This recommendation may result in modifications to subsequent tasks 2.2 through 6.

2.2. Evaluate outlier samples for potential explanations

Purpose and goals

- Statistically compare sampler design approaches (wet/dry and bulk samplers, sampler height, screening)
- Investigate potential causes for outlier samples
- Recommend treatment of outliers to calculate fluxes

Data needs

- Date of screen installation
- Field notes and metadata for outlier samples for Barrus and W. Miller data, namely information documenting presence of insects, leaves, algae
- Raw data from Barrus for paired screen/no screen samplers from Orem WWTP and GSL locations
- Precipitation and wind data from local stations

Analysis

1. From the flagged outlier data in item 1, cross-check against sampling metadata to determine if outliers are associated with (a) sampling methodology and/or (b) sources of contamination and/or (c) other mechanistic explanations (i.e., weather, localized sources)
2. From the flagged outlier data in item 1, evaluate whether outliers co-occur for different nutrient constituents
3. Summary statistics and visualizations (e.g., boxplots) for groups of samples:
    a. Boxplots of flux for sampler design experiments
    b. Boxplots comparing groups of samples: non-outliers, outliers with contamination identified, outliers with no contamination identified, and outliers with no sampling metadata available
    c. Visualizations for samples associated with weather events
4. Statistics
    a. Paired statistical tests for comparing sampler design (e.g., paired t-test or similar depending on appropriate assumptions)
    b. Statistically compare sampler design approaches (wet/dry and bulk samplers, sampler height, screening)

Output

- Tables of outlier samples joined with sampling metadata
- Statistical comparisons of sampler design and among-site fluxes
- Summary statistics and visualizations (see Analysis above)

Decision points

- Inclusion of data from various sampler designs
    - Bulk and wet/dry samplers
    - Sampler height
    - Screened/unscreened samplers
- Type of materials to be considered contaminated vs. not contaminated (e.g., insects, leaves, algae)

- Treatment (inclusion/exclusion, weighting relative to other stations) of outliers for the following scenarios:
    - If sources of contamination are confirmed to be present in the sample
    - If sources of contamination are confirmed to be absent from the sample
    - If no metadata are available
- Recommendation for the processed dataset with data subset that are approved for inclusion in analysis
- Recommendation of areal flux rates

3. Evaluate spatial interpolation among sites and attenuation of fluxes (SP with Tt support)

Purpose and goals

- Estimate the degree of attenuation of atmospheric fluxes moving from shoreline to mid-lake

Data needs

- Literature evidence for attenuation over lakes (acquired)
- Bird Island data (acquired)
- David Richards analysis of spatial interpolation vs. mathematical averaging (report acquired, additional data may be needed)
- Barrus 2021 analysis of Bird Island data

Analysis

1. Evaluate temporal aggregation across sites, with special attention to the order of operations between spatial and temporal aggregation (*Note: analysis will not include a comparison of the approaches but rather an incorporation of the SP-recommended approach following discussion*)
    a. Aggregate spatially, then temporally
    b. Aggregate temporally, then spatially
2. Evaluate spatial interpolation across sites, with special attention to how to deal with sites that differ from others in areal flux (local sources) (*Note: analysis will not include a comparison of the approaches but rather an incorporation of the SP-recommended approach following discussion*)
    a. Spatial interpolation vs. mathematical averaging
    b. Aggregation of central tendency (mean, geomean, median) among sites
    c. Interpret fluxes at Bird Island relative to shoreline samplers
3. Summary statistics and boxplots
4. Time series plots
5. Statistical analysis of fluxes at Bird Island vs. shoreline samplers (paired statistical test consistent with relevant assumptions)
6. Evaluate David Gay review of Bird Island data and implications
7. Analysis of the impact of assumptions for no attenuation and rapid attenuation of loads moving from shoreline to mid-lake (*Note: analysis of spatial interpolation for each individual sampling date will represent an additional level of effort*)

Output

- Summary statistics
- Summaries of flux-to-load conversions based on SP decisions

Decision points

- Order of temporal and spatial aggregation
- Method for spatial interpolation
- Combining or keeping separate G. Williams and W. Miller data
- Recommendation of how to handle Bird Island data
- Recommendation for attenuation, including a central estimate as well as upper and lower bounds

4. Evaluate speciation (SP with Tt support)

Purpose and goals

- Loads of individual chemical species of N and P are needed as inputs to the ULNM
- Identify relative proportions and absolute amounts of N and P constituents making up total atmospheric loads

Data needs

- Previously developed studies and literature that estimate N and P species in atmospheric deposition (acquired)
- Processed data from items 3 and 5 for individual constituents (e.g., nitrate and ammonium in addition to total N loads)

Analysis

1. Summarize proportion of N and P loads made up of individual constituents for literature-based estimates
2. Calculate proportion of loads with directly sampled data, where available

Output

- Summary tables of proportional and absolute loads of individual chemical constituents

Decision points

- Identify if and when chemical constituents in directly sampled data are appropriate to use to assign speciation. Considerations:
    - Holding times
    - Concentrations of individual constituents exceeding total concentrations for an element
    - Comparability of constituents among sampling approaches (e.g., SRP vs. orthophosphate vs. bioavailable P)

5. Constraining Analysis Evaluation

Purpose and goals

- Compile atmospheric deposition estimates from constraining analyses to compare to direct estimates
- Evaluate confidence and uncertainty of constraining analyses compared to direct estimates

Data Needs

- Mike Brett updated mass balance, including updated sediment accumulation rates and carp removal
- Reports and memos of previously completed constraining analyses (acquired)

Analysis

1. Compilation of flux and load estimates from constraining analyses

Output and Decision Points

- Summary of constraining analysis approaches, flux and load estimates, and confidence/uncertainty

6. Determine loading for including in the ULNM

Purpose and goals

- Summarize SP Subgroup recommendations from items 1-6, including a documentation of consensus-derived output and any dissenting perspectives from non-consensus-derived output
- Summarize information from items 1-5 to recommend an estimate of atmospheric loading of N and P to Utah Lake. Includes:
    - Fluxes
    - Attenuation
    - Total load
    - Speciation of chemical constituents

Data needs

- None

Analysis

- Synthesis of items 1-5

Output and Decision Points

- Recommendations memo detailing decision points from items 1-5 and a recommendation for an estimate of atmospheric loading to Utah Lake

TP and DIN Constituents

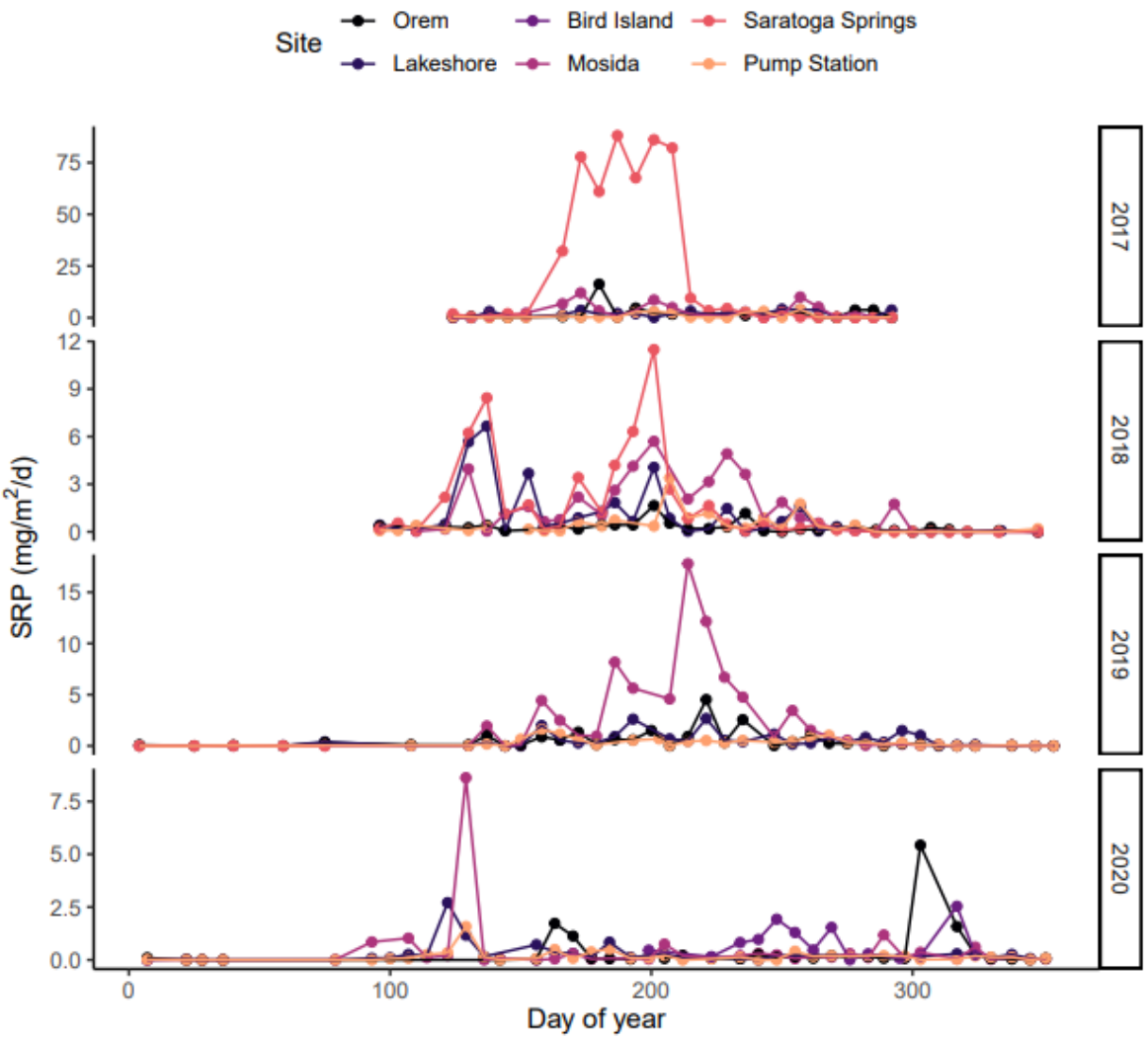

Figure 38. Time series of SRP samples from the raw Williams dataset.

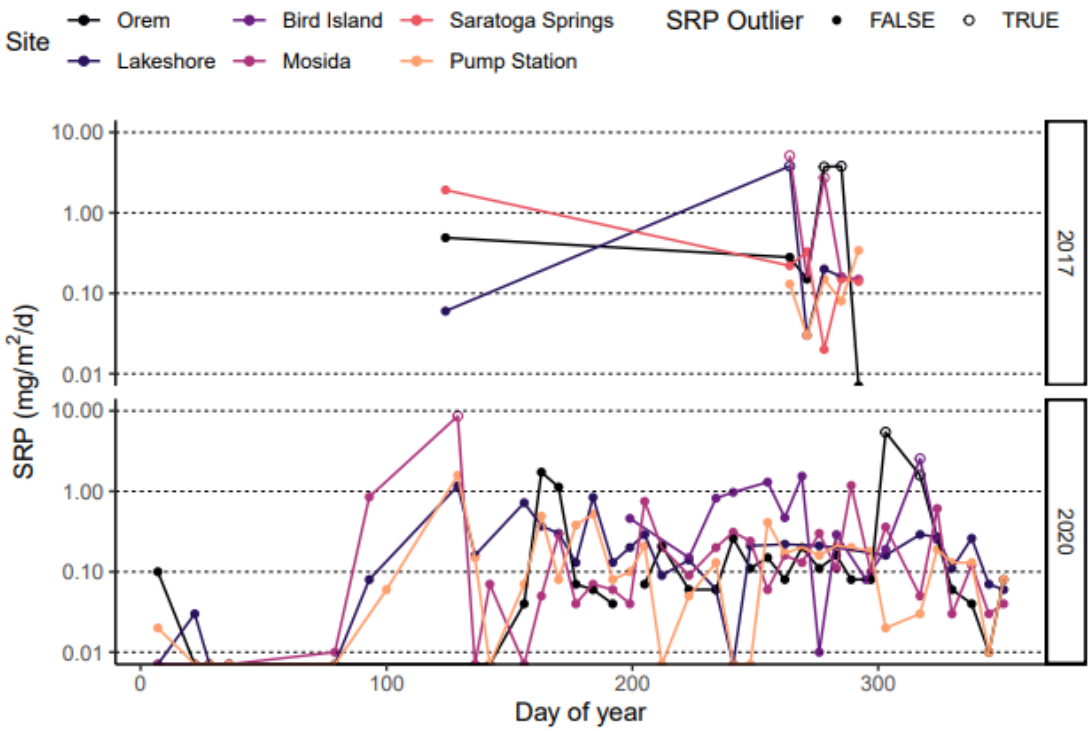

Figure 39. Time series of SRP samples from the processed Williams dataset, excluding any samples that included insect contamination or did not have metadata available.

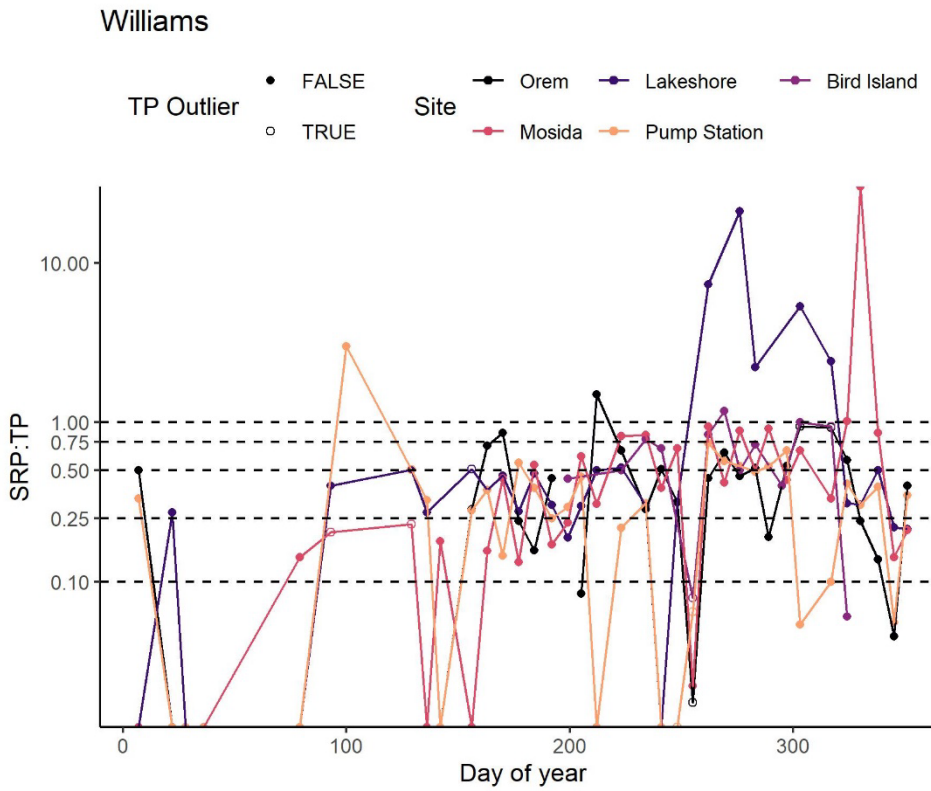

Figure 40. SRP to TP ratios from the 2020 Williams dataset. Values >1 area a functional impossibility because SRP is a component of TP; thus, any values >1 are an analytical QA issue but were not pursued further by the subgroup.

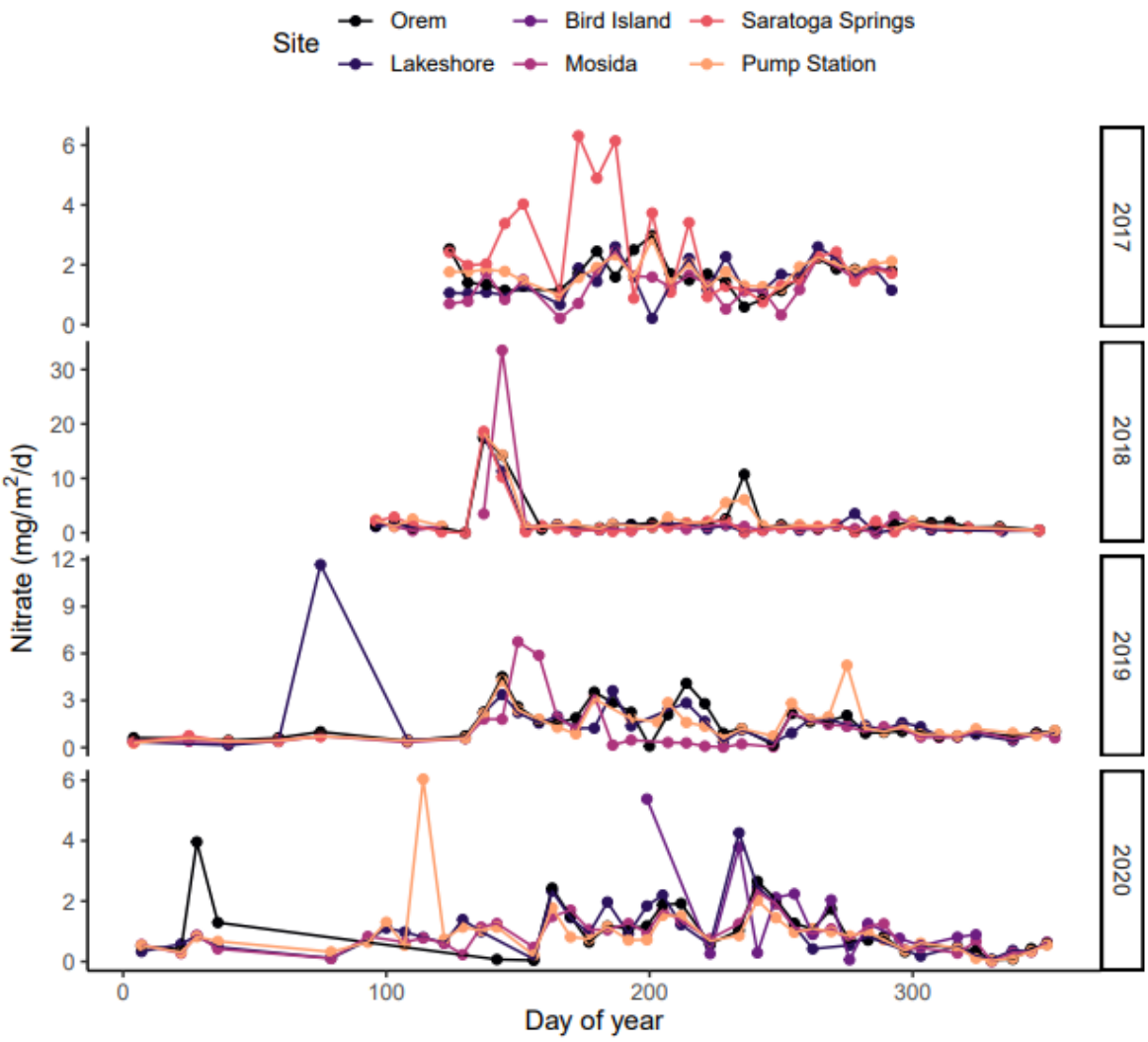

Figure 41. Time series of nitrate samples from the raw Williams dataset.

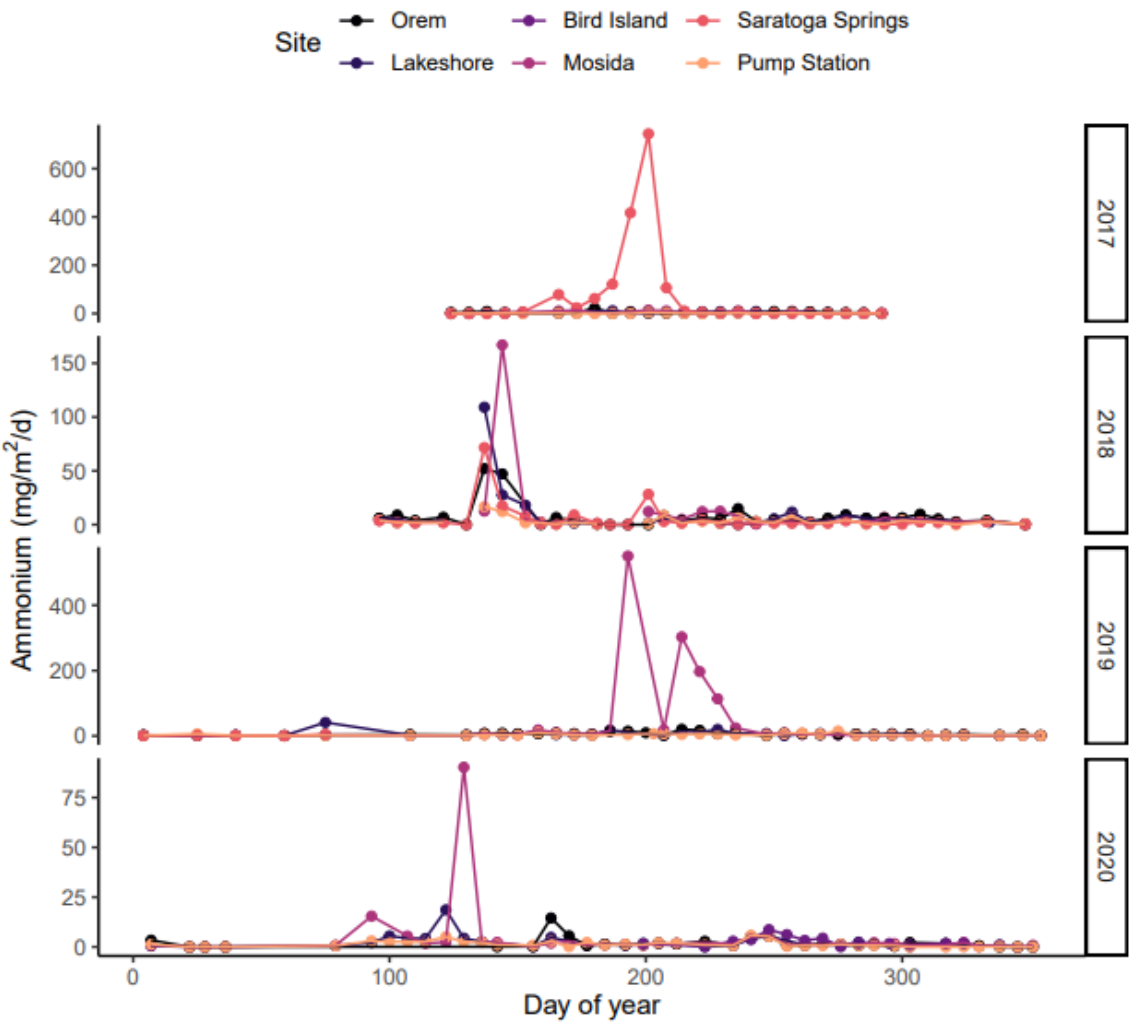

Figure 42. Time series of ammonium samples from the raw Williams dataset.

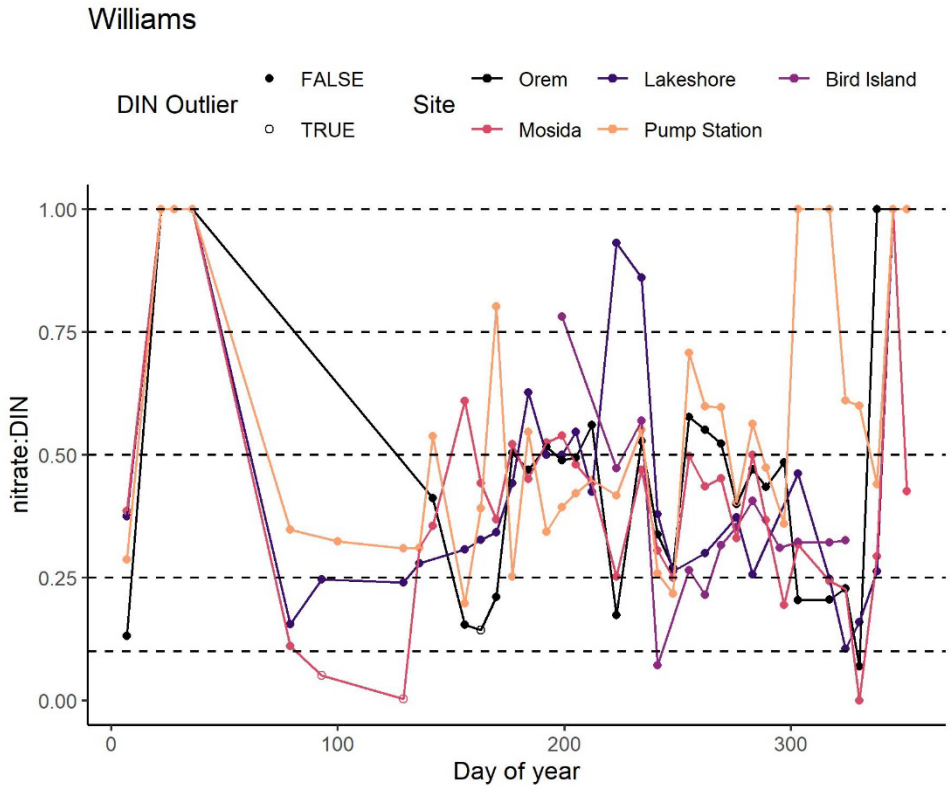

Figure 43. Nitrate to DIN ratios from the 2020 Williams dataset.

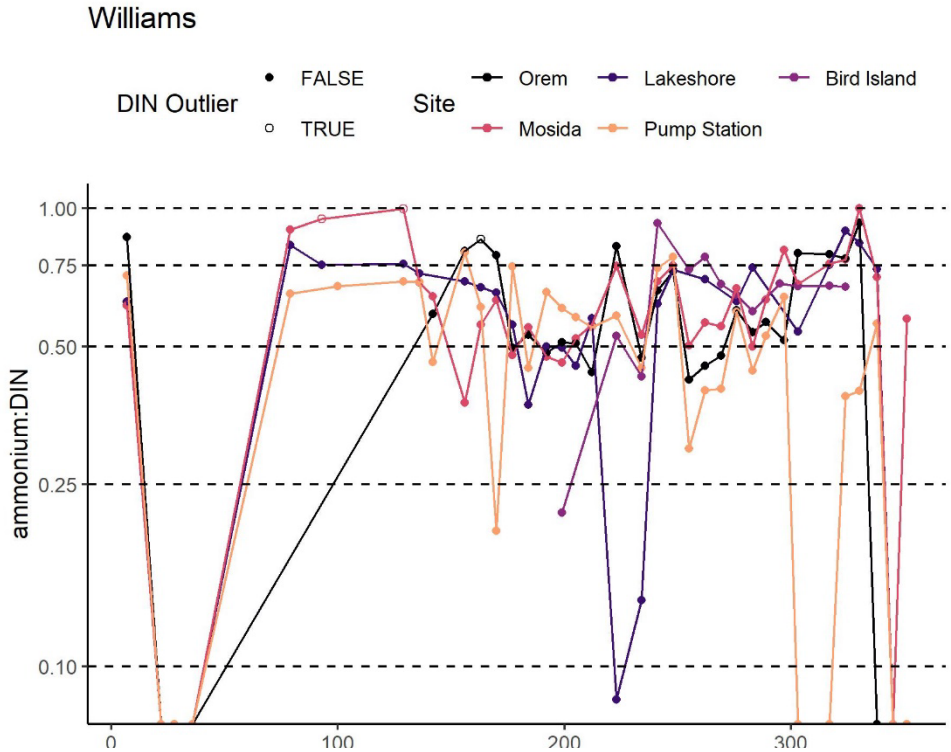

Figure 44. Ammonium to DIN ratios from the 2020 Williams dataset.

Diverging Perspectives Memo and Reference Material

A Critical Evaluation of Discussions, Presentations, and Recommendations by the Utah Lake SP Subcommittee on Atmospheric Deposition

by

Theron Miller

Science Panel and Subcommittee Member

February 2023

Following are clarifications, additional evidence, and deliberations, including those based on published data that refute the recent discussions, presentations and conclusions of the DWQ Utah Lake Science Panel Subcommittee on atmospheric deposition. Many of these points I have made for years, others are more recent.

The paper by Wilson and Serre (2007) reported on transport of NH_3, not P. But even as such, the decline in NH_3 plateaued at about 5 mg/cubic meter at 2000 m. The SP subcommittee needs to acknowledge that our Utah Lake N values are within the range of Wilson and Serre (2007), Brahney (2019), and USGS data surrounding GSL.

However, there is still an important weakness in the Wilson and Serre study. In short, these authors tracked ammonia along a linear transect downwind from several individual hog farms. While measurements tracked attenuation, it was not entirely from settling. Wilson and Serre (2007) sample design ignored the principle of radial jet theory, a published well-known mathematical computation describing the lateral dispersion of point source discharges radiating in a circular pattern outward, such as in a lake. This radial pattern serves to dilute/disperse laterally the concentration/intensity as distance extends from the source, much like the radial pattern of throwing a stone onto a lake surface. Therefore, the SP subcommittee conclusions based on Wilson and Serre are faulted by not accounting for radial jet theory. That is, ammonia was dispersing laterally at least as much as it was dispersing and settling longitudinally. Consequently, the decline in ammonia concentrations was not entirely due to particle settling, but rather to horizontal diffusion and dispersion following radial jet theory. Moreover, according to the SP slide deck, this attenuation to about 5 mg/cubic m was applied to regional dust data on Utah Lake rather than the local dust that it was supposed to represent. We all need to accept that regional dust can include additional contributions from local sources, hence characteristics of transport include a reconfigured blending of distant and local sources, depending upon size fraction, particle structure, as well as wind patterns. As such, the attenuation pattern for regional dust used by the SP subcommittee was likely misapplied. Recently, to adopt the attenuation pattern of Wilson and Serre (2007) may be inappropriate as it only refers to local simple ammonia values and not the complex of dusts surrounding Utah Lake. It could be construed by outside observers that this was just a matter of convenience on part of the SP subcommittee (i.e., only ammonia attenuation downwind of a CAFO) to show that attenuation is as rapid as possible in order to oppose any data that demonstrates that fine particles (likely up to 10 um; characteristic of Great Basin playa dust) can be transported at much greater distances that 2000 m.

Recently, Scott Daily (DWQ) mentioned that the source of P and N at Mosida could be the nearby dairy. However, the dairy is actually located 5500 meters away, although some drying ponds associated with the dairy are about 1200 m distance. NADP guidelines state that AD samplers need to be >500 m distance needed to be considered valid. Nevertheless, Barrus et al. (2021), removed two of 39 P and three of 39 N samples at Mosida as outliers to address this problem. After removal, the P results were lower than the averages of the other four sites and

the average N was near the average of the other sites. Thus, if at all, there was very little influence from the drying ponds on the Mosida site data.

In addition, another panel member stated that there are "thousands and thousands of birds on Bird Island". This was apparently accepted as fact by the rest of the Subcommittee without evidence and is highly conjectural. Birds would virtually have to sit on top of each other to fit "thousands and thousands" on this tiny ¼ acre island that frequently gets inundated by waves. Frequent wave inundation of the island also suggests that the accumulation and mobilization of dust particles is insignificant to non-existent to be a local source. Therefore, while the panel believes that there is some type of point source emanating from Bird Island, there is no scientific support for such an assumption, or for removing this data. Another example, the average of ammonia from the Bird Island site, the only volatile compound in the study, remains near the values for the other sites. Elevated values for N and P at Bird Island are most likely only a reflection of the elevated N and P at Mosida which is directly upwind of the afternoon prevailing wind coming out of the SW. Moreover, I recently presented a logical hypothesis implicating converging daily prevailing breezes, down canyon early morning breezes from Spanish Fork and Provo Canyons, passing across the urban areas, traveling passed the airport (see windrose) and on across the lake. These winds are immediately followed by the prevailing SW midday and afternoon breezes heading directly across the lake (see windrose), and toward the suburbs as indicated by Goodman et al. (2019). These breezes converge and subside in the central portion of the lake (the coolest part of the valley) as demonstrated by the nearly daily inversions that develop in the very bottom of the valley which is directly over Utah Lake. Hence, this inversion is comprised of fine particulates accumulated from both directions. Moreover, elemental analysis by Telfer et al. (in preparation) identifies the Cherry Creek area (about 10 miles SW of Mosida) as being most similar to all of the shoreline sites and Bird Island. Notably, this site is directly in line with the Sevier Lake playa- which was the dominant source of urban dust in Provo, identified by Goodman et al. (2019). This point needs to be firmly established into our collective understanding of AD.

With respect to the distribution of the size range of particles, the complementary nature of the different types or fractions collected from different samplers of AD has been described in a well-documented recent white paper by Williams (attached). Moreover, this report has been reviewed by Dr. David Gay, Director of the NADP. He has expressed his support for the complimentary nature of the fractions described by Williams and is expected to provide a written comment letter by February 20.

Comments on the SP Subcommittee "Constraining" document:

Dr. Theron Miller comments are highlighted in blue.

Constraining Document: "Areas with extreme urban pollution and high rates of biomass burning are anticipated to have the highest concentrations of P deposition due to the high P concentrations of combustion products (Mahowald et al. 2008, Brahney et al. 2015)".

Dr. Miller Comments: This statement is inaccurate and misleading. In fact, Mahowald et al. (2008) states that combustion composes only about 5% and for only some locations around the world. Rather, 82% of deposition is mineral aerosols – which is much closer to the dust sources around Utah Lake (Goodman et al. 2019).

Constraining Document: "A deposition rate of 1000 mg P/m2/yr is 9.5 x the standard deviation above the global max. A deposition rate of 500 mg P/m2/yr is 7x the standard deviation above the global mean. Given TP deposition measured worldwide, values above 175 tons of P to Utah Lake need an explanatory mechanism, which is currently unknown."

Dr. Miller Comments: We have provided an explanation, please read our material. We have an abundance of data through multiple years, including the occasional wind and dust storms mobilize dusts from the hundreds of square miles of playa dust that surround Utah Lake. This is not typical of any deserts or otherwise in the worldwide data base. In addition, the accumulation of dust over the lake in the near-daily inversions has been discussed before and again, above. In addition, the recent white paper by Williams explains how most samplers are designed to sample one of the three fractions of AD. Read the Williams White Paper for details.

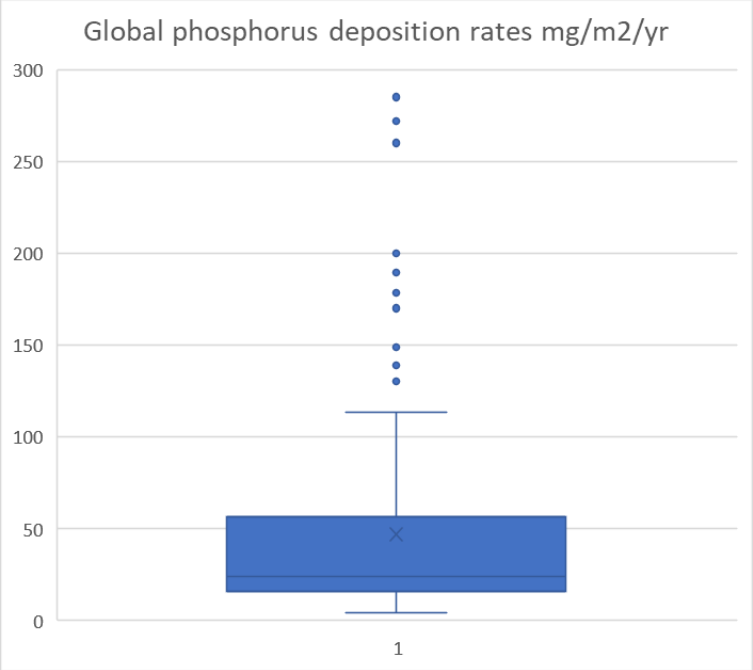

Figure 1. Distribution of measurements of P deposition worldwide. Data include a range of landscape types, from remote to urban, agricultural, tropical, and near other shallow polluted lakes (e.g., Lake Taihu). From TetraTech.

Constraining Document:

- Biological Material is on average 1% P, or 10,000 ppm.
- Average Wasatch Front long range 'Regional' dust is 0.09% P (900 ppm) based on 12 samples (Reynolds et al. 2014, Brahney and Skiles, *unpub*),

- Local playas are reported to be similar at 1000 ppm or 0.1% P, (n=?) (Williams et al. 2022).
- Distal playas are on average 2152 ppm P
- Local urban dust (Provo, SLC, Ogden) are on average 2959 ppm P (n=12), Provo average dust P is 3916 ppm (n=4)
- The average of all regional and local dust samples is 2058 ppm (n=64)

Dr. Miller Comments: Goodman and Carling noted the enrichment of P in urban dust but had no explanation. Throughout their paper Goodman et al. (2019) noted that the urban dust was 90% similar to the Sevier Lake playa dust to the SW, yet no explanation was offered. Here's the likely explanation: Urban environments are characterized as hardened surfaces with very little opportunity for infiltration or washing off, except for the occasional rain. Rather, dust accumulates on road surfaces, parking lots, gutters etc. Traffic, wind, and other disturbances frequently and randomly remobilizes this material – allowing transport for various distances, depending on wind direction, velocity, and particle size. This accumulation/enrichment may proceed for weeks, between rainstorms.

Why did the "Constraining" authors decide to just average regional and local dust with no defined reason and place more weight on regional dust from great distances (i.e.. averaging regional dust (based on 12 data points from hundreds of miles away) than with local dust. Also, why include data from Logan, Ogden and SLC sites with the Provo site. The Provo site is 33% greater than from other Wasatch front sites that are 50 to 215 miles away? This only dilutes the Provo site, which is actually much more representative of the influence on nearby Utah Lake.

Constraining Document: "No one knows the true deposition rate to Utah Lake. We again can create unrealistic upper and lower bounds. The regional dust deposition rate is 6 $g/m^2/yr$ as measured (Brahney et al. 2019 and citations within)"

Dr. Miller Comments: As described, this value is only ascribed to far-range regional AD, which is only a portion of total AD. Thus, it is not comparable to the total of upwind regional, local, bulk, and precipitation washout samples. The Brahney samples were simply not collected near Utah Lake. Also see Williams white paper.

Note that the recent work of Telfer et al. (in preparation) identified a much closer source of dust (Sites 4 and 8; Figure 3 below) than the sources identified by Goodman et al. (2019). Moreover, these samples were highly similar to the dust samples filtered from the wet/dry samplers, including the samples from Bird Island. The Bird Island samples were more related to Cherry Creek dust (10 km from the Mosida sampler and 23 km from the Bird Island sampler; Telfer et al. in preparation) and its deposition by contact. There is much more discussion on the fraction of AD that is composed of regional dust from Dr. Williams' analysis (attached).

Constraining Document:
Deriving an associated dust deposition rate:

<u>Bounding information:</u>

- Biological Material is on average 1% P, or 10,000 ppm.

- Average Wasatch Front long range 'Regional' dust is 0.09% P (900 ppm) based on 12 samples (Reynolds et al. 2014, Brahney and Skiles, *unpub*),
- Local playas are reported to be similar at 1000 ppm or 0.1% P, (n=?) (Williams et al. 2022).
- Distal playas are on average 2152 ppm P
- Local urban dust (Provo, SLC, Ogden) are on average 2959 ppm P (n=12), Provo average dust P is 3916 ppm (n=4)
- The average of all regional and local dust samples is 2058 ppm (n=64)

*Urban ground level dust will not travel over the entirety of the lake

Dr. Miller Comments: Apparently, the SP subcommittee authors have not carefully read Goodman et al (2019). Nor have they witnessed the near-daily inversions that cover the entire lake. 90% of urban dust in Provo is of similar composition to the Sevier Lake playa dust. Moreover, the fact that it is enriched before it enters a sampler on top of the Geology building at BYU proves that it is re-mobilized after it is enriched, so its physical nature likely has not changed. If it is the accumulated and resuspended playa dust from the Sevier Lake playa, as reported by Goodman et al. (2019), it has already travelled long distances (>100 km). For example, if they measured this "urban dust" at the top of the BYU geology building at the edge of the mountains (which experiences daily downslope breezes, heading toward Utah Lake), the" Constraining" authors have made an incorrect assumption about the distance urban dust can travel - similar to Brahney's incorrect assumption that the urban dusts extend only 200 to 600 m over the lake – which is actually less than 10% of the lake surface. It should be recognized that dust from a local gravel road is not similar to dust that has already travelled more than 100 km and temporarily settled in urban Provo (Goodman et al. 2019). If it's 90% the same dust, it is logical to hypothesize that it travels downslope and back over the lake, also as an aerosol, as the inversion develops or strengthens. We will be testing this hypothesis as soon as it is safe to travel on the lake.

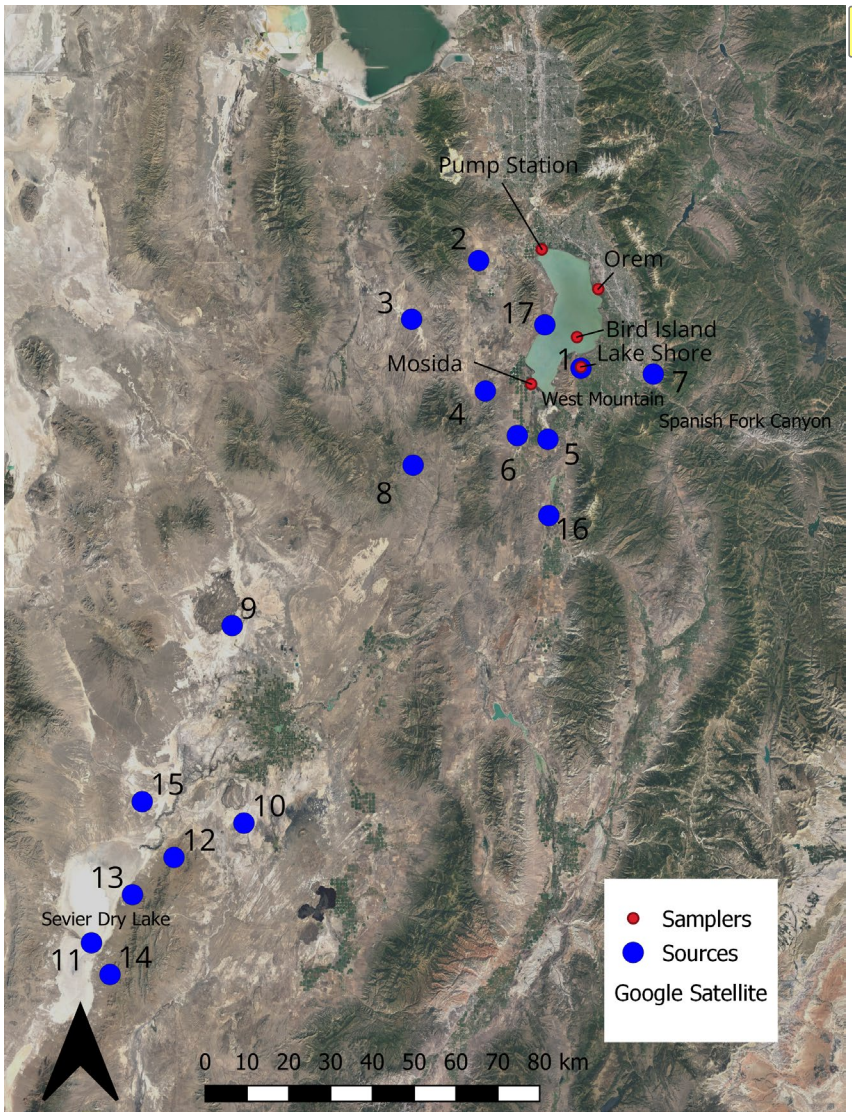

Figure 3. Samplers were placed around Utah Lake with one sampler on Bird Island. The dust source locations were chosen at the southern half of Utah Lake and in a southwest direction towards Sevier Dry Lake. Sampler abbreviations: PS=Pump Station, BI=Bird Island, LS=Lake Shore, MO=Mosida. Source numbers: 1=Lake Shore, 2=Eagle Mountain, 3=5-Mile Pass, 4=Chimney Rock Pass, 5=Goshen WMA, 6=Elberta, 7==Mouth of Spanish Fork Canyon, 8=Cherry Creek, 9=Fumerole Butte, 10=Sunstone Knolle, 11=Sevier Dry Lake, 12= Cricket Mountain, 13=White Hills near Sevier Lake, 14=Mid-Sevier Lake near road, 15=Highway 6 South of Delta, 16=Burraston Ponds, and 17=Miners Canyon. (From Telfer, in preparation)

To revisit the "Constraining paper"

Constraining Document: "Average urban dust deposition rates in Utah are 40.5 g/m^2/yr (range 25-57 g/m2/yr) (Goodman and Carling 2019, Scholz and Brahney 2019)[n = 37].

"These values are similar to urban measurements made elsewhere in the western US and world (Lawrence and Neff 2009, Brahney et al. 2015, Brahney 2019 and references within).

Given that urban areas receive the greatest dust deposition rates (from intense local generation."

Dr. Miller Comments: No, actually it's local enrichment/accumulation of dust that arrived from distant playas. The enrichment of urban dust P is due to the accumulation of dust from the original sources (southwest playas; (Goodman et al. 2019). The continued accumulation of dust combined with the local turbulence, (e.g., cars passing by on hardened surfaces), that resuspends this very light material.

Constraining Document: "… that dust deposition rates will attenuate away from their ground level source, it can be expected that the average dust deposition rates to the entirety of Utah Lake should not be greater than 40.5 g/m^2/yr."

Dr. Miller Comments: This is highly unlikely. That urban sources are from playa dust 20 to >100 km away demonstrates that long-range transport has already occurred. The realization that these urban dusts originated from distant playas can now support the evidence that dust can travel back downslope and across the lake, including Bird Island, as evidenced by the frequent inversions – not just 600 m from town. Again, the panel has ignored the fact that inversions, obviously comprised of local dusts, spread over the entire lake surface at the bottom of the valley, on a near-daily frequency (transported by the local downslope breezes – as indicated by the Provo airport windrose),

Moreover, we verified each weekly visit that there was no evidence of bird droppings or insects in the bucket, on the screen or on the table surfaces. This is logical in that the water birds that frequent Bird Island (predominantly California Gulls, Franklin Gulls, Caspian Terns, White Pelicans) have webbed feet that are poorly designed for grasping and perching on thin sampler bucket rims. The distance from Utah Lake's shoreline to Bird Island precludes passerines (perching birds) to identify as a destination or to risk predation during the journey.

Also, there is no evidence supporting the assumption that Bird Island acts as its own point source. It's just speculation to support the decision to throw out the data. We will test this hypothesis during the 2023 season using mobile air samplers. If one examines the N (and the P) data, Bird Island data is very similar (not significantly different) to the shoreline data (i.e., the best chance for being a point source would be elevated values for volatile compounds such as ammonia – but data doesn't support this. And P has no gaseous phase. The similarity of urban dusts to distant playa dusts (Goodman et al. 2019) and the similarity of dusts deposited in the Bird Island sampler to Cherry Creek dusts (Telfer in Preparation) also does not support the conjecture that Bird Island functions as its own point source.

Constraining Document: "Data assimilated from global observations indicate that only a few sites in the world have deposition rates greater than 100 g/m^2/yr, and these sites occur is desert areas such as the Gobi Desert in China as well as Libya and Niger in the central Saharan Desert. Areas that receive approximately 50 g/m^2/yr include the Loess Plateau in China, regions of Israel, and Phoenix, Arizona."

Dr. Miller Comments: Yes, but these locations are not affected by nutrient-rich playa dusts originating in the middle of an ancient lake, Lake Bonneville, that resided in the middle of even

more ancient and uplifted (and eroding) 300 to 500 million year old shallow sea sedimentary deposits.

Constraining Document: "No one knows the true deposition rate to Utah Lake. We again can create unrealistic upper and lower bounds. The regional dust deposition rate is 6 g/m^2/yr as measured (Brahney et al. 2019 and citations within)."

Dr. Miller Comments: This is not comparable to the total of regional, local bulk and precipitation washout samples. See Williams white paper, attached.

Constraining Document: "…and an upper bound of 40.5 g/m^2/yr as the urban rate. As above, neither is likely given that the average dust deposition rates (for the full lake area) will be somewhere between the two boundaries."

Dr. Miller Comments: Not necessarily, as I wrote above.

Constraining Document: "Canyonlands, a well-known dust producing region in arid southern Utah provides a median deposition rate, which is 29 g/m^2/yr (Reheis and Urban 2011, Brahney et al. 2020).

Dr. Miller Comments: These samples were not collected near Utah Lake.

Please acknowledge that Utah Lake and GSL are in the middle of a giant playa - with huge amounts of well-known P-rich dust emissions. For example, compare to the Owens Lake playa which is about 0.0000001 the size of playa as that surrounding Utah Lake and GSL(e.g.. see our SAP). Similar dust storms have been observed blowing over Utah Lake and GSL. Read Reheis (1997), another paper that was omitted in the Brahney white paper. Table 1, in that paper reports dust deposition rates of 7.8 mg/m^2/day to more than 2100 mg/m^2/ day. Converted to an annual rate this equates to 2.847 g/m^2/yr to 792 g/m^2/yr – a little higher (more than an order of magnitude) than your 40.5 g/m2/yr "unrealistic" upper bound from regional sites. To follow through, even at 1% P this will dwarf all SP Subcommittee estimates provided in Figure 1. And this is exactly comparable to playas surrounding UL as the dust source was the Owens Lake playa formed from a century of diverting tributaries to LA.

Also, "Canyonlands is a well-known source of dust"? I don't agree. (reference?). Where are lake-deposition-based, fine dust-producing playas in Canyonlands National Park. I have been there many times. Not too surprising, it's full of canyons that trap dust and sediments, and is completely different from the geography and geology surrounding Utah Lake. We have presented considerable evidence contradicting or rather, supplementing, the Brahney dataset. For example, Brahney ignored an important paper (Jassby et al. 1994) which demonstrates that fine particles can travel 20 km, to the middle of Lake Tahoe with only a 12% reduction in deposition and which was not a statistically significant reduction. Notably, adjusting for lake size, the 4-yr study by Jassby et al. (1994), results in 150% of the SRP as that purported to occur on Utah Lake by Brahney (2019). This is surprising in that Lake Tahoe is in a forested alpine basin at 6500 ft elevation with the only sources of dust being the Central Valley of California (80 miles away), and which must travel over the 9500-ft Sierra Nevada mountains or the Mohave Desert of

Southern California or Southern Nevada, (about 200 miles away). This 4-yr study, with hundreds of samples, simply contradicts Brahney's original attenuation estimates of 200, 400, 600, and now 2000 m for regional dust from the eastern shoreline. The panel needs to be using actual comparable data rather than picking unrepresentative data or making conjecture or rates just to put arbitrary "constraints" on attenuation. It is inappropriate to ignore relevant data (such as Jassby et al. (1994) and Reheis, 1997), especially when playa dust located >100 km SW of Utah Lake is the dominant dust in urban Provo, on the opposite side of the lake, using non-peer-reviewed estimates of P transport across the lake while attempting to ignore peer reviewed data from Barrus et al. (2021). I suggest that as unbiased scientists, we need to reconfigure this whole paradigm.

Constraining Document: Goshen Bay sedimentation rate 1.7 mm/yr, *Mitch Power freeze cores north of Provo Bay show similar rate.

Dr. Miller Comments: This has not been actually quantified or peer-reviewed. Freeze cores don't have that level of resolution as sediment traps. We are all aware that sediment mixing and resuspension in shallow lakes (for which Utah Lake is famous) from frequent winds and carp bioturbation precludes accurate measurement of sedimentation rates. Because sediment traps were not used, this is questionable data.

Constraining Document continues:

Provo Bay sedimentation rate: 2.6 mm/yr
Bird Island sedimentation rate: ~1 mm/yr

Dry density of Utah Lake surface sediments at Goshen Bay: 0.7 g/cm3
Dry density of Utah Lake surface sediments at Bird Island 0.55 g,
Dry density of Utah Lake surface sediments at Provo Bay: 0.5 g/cm3

The above information is consistent with modern sedimentation rates measured in other waterbodies throughout North America (Brothers et al. 2008)(Appendix A).

Dr. Miller Comments: Possibly, but sedimentation on GSL is 3.5 – 4.5 mm per year – in the middle of GSL (USGS Se study; using sediment traps). Given the several years of the SP's existence, the SP Subcommittee now needs to acknowledge that Utah Lake and GSL are not similar to most other lakes in the world, particularly in regard to AD, morphology and geography. Utah Lake and GSL are in the middle of a unique dust-filled giant playa. For example, compare these to Owens Lake which is about 1/100000 the size of playa as that surrounding Utah Lake and GSL, see our SAP.

Constraining Document continues: One would anticipate areas closer to the shore and thus closer to sediment sources and areas with higher production, would have greater sedimentation rates.

Dr. Miller Comments: This assumption ignores the principle of sediment focusing which distinctly occurs in shallow GSL.

Constraining Document Continues: In addition to catchment and production sources of material for sedimentation, authigenic calcite makes up a sizeable portion of the sediment accumulation.

Using estimated AD deposition rates from 5 to 350 Tons we can determine plausible AD deposition rates of P given that deposition rates should (at least) not exceed measured sediment accumulation rates in all parts of the lake

Dr. Miller Comments: Sediment accumulation rates used here are not accurate. They were not measured.

AD Tons of P to Utah Lake	0.55 g/cm3	0.64 g/cm3
	mm/y	mm/y
5	0.03	0.02
25	0.13	0.11
75	0.39	0.33
175	0.91	0.78
350	1.82	1.56

The constraining document continues: "If we again assume a dust deposition rate of 29 g/m^2/yr, we arrive at a sediment accumulation rate of 0.17-0.28 mm/yr, or 10 to 16% of the measured sediment accumulation rate"

Dr. Miller Comments: What happened to the 1.7 mm reported by Mitch Powers?, whose data, I mentioned, is 1.5 orders of magnitude less than MEASURED (using sediment traps) GSL sediment accumulation rate. And 1.5 orders of magnitude less than MEASURED dust deposition from the Owens, Lake Playa. If we use the GSL MEASURED rate, and even close to that measured from the Owens Playa dust emissions there is plenty of deposition to cover the 350 tons of P to Utah Lake.

Concerning Speciation

From Dr. Wood Miller's data (approximately 2000 samples):

The Dr. Wood Miller data set includes bulk samples but uses quite a different method from other bulk samplers (i.e., Bunt cake tins or plastic totes with the bottoms generally covered with marbles) which may or may not have been analyzed for both Total P and ortho-P. Throughout all the sample sites and the entire sampling period, the proportion of ortho-P ranged from 41 to 62% of the total P (see inserted "pictures" of data tables). A large amount of the total P is biologically available.

Jassby's et al. 1994 work on Lake Tahoe resulted in SRP to TP ratios of 44 to 47% (Table 4 below). Jassby et al. 1994 and Wood Miller's data agree quite well. Yet, both are quite different

from the summary by Tetra Tech which uses a value of 33 to 37%. Where does this data come from?

Table 4. Ratio of Dissolved Inorganic Fractions of N and P to Total N and P at Ward Lake Level Station

Nutrients	From	Period	Days	*n*	Ratio mol : mol
DIN : TN	wet	Oct. 31, 1991 to Sept. 1, 1992	185	26	0.76
	"dry"	Nov. 6, 1991 to Sept. 30, 1992	288	32	0.24
SRP : TP	wet	Nov. 21, 1991 to Sept. 1, 1992	198	28	0.44
	"dry"	Dec. 11, 1991 to Sept. 30, 1992	288	31	0.47

Period, dates spanning the measurements; days, total number of days during the period actually measured; *n*, number of separate sampling intervals into which these days are divided.

Dust content of ca and mg

Mitch Hogsett (Science Panel co-chair) stated that the majority of P in playa dust would be bound to calcite.

Dr. Miller Comments: This is likely not true. Dust data from Goodman et al. 2019 found Mg to be 2X to 3X more concentrated than Ca in the playa dust and Carling et al. and Randall et al. has reported that 40% of sediment P is associated with Fe. In short, redox reactions between the high concentrations of Fe/Mg and P are occurring. This was clearly illustrated by Hogsett et al. (2019) where they report that 1500 tons of P is potentially mobilized from the sediment per year. This was the conclusion from Hogsett's experiment using DO chambers, in contact with the sediment surface, to near 0 mg/L DO – an experiment illustrating the effect of redox reactions on P speciation. This value dwarfs atmospheric deposition of P, POTW discharge stormwater runoff and tributary contribution combined. Large releases of sediment P during hypoxic events are not unusual. The release of phosphorus from bottom sediments can contribute up to 99% of the total P pool in shallow lakes (Bostrom et al. 1988, Jensen and Andersen 1992; Hullebusch et al. 2003). Unfortunately, Hogsett's paper, including the contribution of P and N, have not been discussed by the SP and therefore, I am concerned that this large contribution of nutrients to the water column – likely causing the blooms, as Michael Brett pointed out, will be underrepresented.

There is another important measurement within the Jassby et al. (1994) paper. Dry deposition data indicated that attenuation of SRP from AD included a reduction by about 12% from a shoreline sampler to a sampling bucket located 20 kilometers (12 miles) from shore. This value is not significantly different from the shoreline data. For comparison, the sampler at Bird Island was only about 6 kilometers from the shoreline. In turn, there was no attenuation of P in the AD at Bird Island as compared to the shoreline sites, a value quite comparable to the 20-km range in the Lake Tahoe Study. Also, particle sizes were notably smaller than from other sampling sites – indicating that they can travel long distances (See Williams white paper).

Another important comparison: dry deposition of P on Lake Tahoe was about 3.5X greater than wet deposition (Jassby et al. 1994). Dry deposition on Utah Lake is about 3.5X greater than wet deposition (Olsen et al. 2018).

However, Jassby et al. (1994) noted that AD collected in 2-m "snow tubes", used to estimate wet deposition rates during winter, were quite different. P measured in the snow tubes at the 20 km site fell off by 90% compared to the shoreline site. There is no explanation given – neither by the authors nor Tetra Tech. After "Google Scholaring" for about 45 minutes, I could not find a peer-reviewed paper that addresses the difference in wind-driven snowfall (in a horizontal direction) across flat surfaces such as ice cover vs snowfall in rugged or forested terrain such as that surrounding Lake Tahoe. This is related to the idea of snow fences throughout the high plains of Wyoming – allowing snow to settle rather than continuing to drift horizontally. The point being that snow is much more likely to settle in the wind-protected rough, forested zones around Lake Tahoe (falling vertically into the snow tube), than on the ice surface on a 40 by 70-kilometer lake – where comparatively, any breeze will blow the snow horizontally across the opening of the snow tube rather than allowing it to fall in it. I have witnessed this effect personally during my research on the ice-covered lakes in the boreal forest of Northern Alberta. Lake surfaces would often be snow-free while several feet of snow would accumulate within the adjacent aspen forest. This was particularly true for the larger lakes.

In conclusion, I have provided additional evidence for supporting the Williams and W Miller data, reports and publications. At the same time, I have provided substantial published data and other scientific measurements that dispute many of the assumptions used to cull or otherwise ignore Williams and W Miller's data and particularly when the panel has chosen to impose an unrealistic attenuation pattern on the lake. The empirical evidence just doesn't go there. Finally, I urge all panel members to read the attached white paper by Williams that presents a logical and scientifically supported arrangement of ALL data presented that describes how these different sampling strategies actually supplement or complement each other in an additive manner – rather than contradict each other.

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Atmospheric Deposition of Nutrients to Utah Lake:

Process and Research Overview

Developed for:
Wasatch Front Water Quality Council
Leland Myers, Project Manager

Developed By:
Gustavious Williams, Ph.D.

February 2023

Executive Summary

In this paper, we classify atmospheric deposition (AD) into three different processes: settlement (dust), contact, and washout. Settlement occurs when large particles, 10 – 100 μm leave the atmosphere due to gravity. They settle on the ground and are only resuspended by a strong wind or mechanical action. Contact refers to smaller particles, less than 10 μm (PM10), and especially less than 2.5 μm (PM2.5) which do not settle (in general) and only leave the atmosphere when they contact a surface Washout refers to particles that are washed out of the atmosphere during a precipitation event. This includes dust (> 10 μm), fines (< 10 μm), and gases. For all three processes, if the particles come in contact with the Utah Lake surface, they are captured and not resuspended, they stick when they contact the water surface.

Using this classification, we can describe nutrient AD using the following equation:

$$AD_{total} = AD_{dust} + AD_{contact} + AD_{precip} \quad \text{Eq 1}$$

Where AD_{total} is the total nutrient AD on Utah Lake, AD_{dust} is the nutrient AD from settleable dust, $AD_{contact}$ is the nutrient AD from fine particles less than 10 μm that are deposited by contact with the water surface, and AD_{precip} is the nutrient AD from materials washed out of the atmosphere from a precipitation event.

We have results from separate studies of nutrient AD on Utah Lake, each focusing on a different type of deposition, settlement (AD_{dust}), contact (AD_{total}), or washout (AD_{precip}). Brahney [1] performed a literature review and estimated that AD_{dust} is in the range of 2 to 9 tons/yr. Miller (unpublished) collected 850 samples around Utah Lake and measured concentrations in rainwater and estimated AD_{precip} of 88 to 142 tons/yr. Barrus, *et al.* [2] evaluated 306 samples collected around Utah Lake and estimated that the total AD (AD_{total}) was between 133 to 262 tons/yr. Using these estimates, we can conclude that AD from fines suspended in the atmosphere ($AD_{contact}$) ranges from 36 to 43 tons/yr, depending on which of the above numbers are used.

Based on these calculations, this means that the AD from dust is only 1.5% to 6.8% of the total nutrient AD. This is supported by recent work by Telfer (unpublished) who measured dust concentrations in samples around the lake and found minimal dust, with annual dust deposition rates of 2.14 to 5.85 g/m^2/yr. These rates are similar to, but significantly lower than those reported by Brahney [1]. However, these samples were not designed to measure dust, some samples were discarded before being measured, and any soluble dust was not measured, so these numbers are reasonable.

The Utah Lake AD studies initial appear to contradict each other because of the wide range of AD estimates. However, when considering that AD is driven by different processes, contact, dust (settlement), and precipitation, and that each study mostly measured only a subset of the total, it is clear that the studies are not contradictory, but rather complement and strengthen each other.

Based on this analysis, we conclude that an annual AD TP loading of rate of 250 tons/yr to Utah Lake is accurate. However, in consideration of the range of findings and potential implications, we propose 150 tons TP/yr could be used as a consensus-based value for evaluation.

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Atmospheric Deposition of Nutrients to Utah Lake:
Process and Research Overview

Gustavious Paul Williams, Ph.D.

Background

Particulate Matter

Particulate matter in the atmosphere (also called PM or particle pollution) is a complex airborne mixture of solid particles and liquid droplets. Atmospheric particle size is generally reported in micrometers (μm) or 10^{-6} m. The particulates in the atmosphere can range in size from a few nanometers to several micrometers. Though PM ranges widely in size, it has been divided into two categories based on diameter. PM2.5 are particles with a diameter smaller than 2.5 μm and are also called fine particles PM10 are particles with a diameter between 2.5 μm and 10 μm and are also called inhalable coarse particles. Particles larger than 10 μm (e.g., sand and large dust) are not regulated by EPA (https://health.utah.gov/utahair/pollutants/PM)

Particulates in the atmosphere are composed of a mixture of gases and particulates such as fumes, smokes and other small solid and liquid particles. One common set of gases relevant to nutrient deposition are nitrogen-oxygen species typically called NOx. NOx is mostly anthropogenic and a major contributor to atmospheric pollution and can be notices as a brown haze during summer months. NOx reacts with other pollutants to form fine particulate matter in the atmosphere [3]. The process of NOx formation from organic compounds involves the reaction of nitrogen-containing volatile organic compounds (VOCs) with atmospheric ozone in the presence of ultraviolet (UV) light. This reaction produces nitrogen oxide radicals that further react with other atmospheric species to form nitrogen dioxide (NO2) and other species. NO2 is a key component of photochemical smog, which is a type of air pollution that is associated with urban and industrial areas. These compound form particulates, with most of the nitrogen compounds present as the ammonium salts in particulate form, except for ammonium nitrite which is a gas.

Atmospheric Particulate Settling

The way particulates settle in the atmosphere depends on their size and weight, with larger particulates settling faster than smaller particulates. For example, dust particles may settle within a few hours, while smaller particles, like PM2.5, can stay in the atmosphere for days to weeks.

Hinds*, et al.* [4] state that particle size is the most important parameter for characterizing aerosol behavior. They show that particles with equivalent diameters of 0.1, 1.0, 10, and 100 μm settle in perfectly calm air at $8.8x10^{-7}$, $3.7x10^{-5}$, and $3.1x10^{-3}$, and $2.5x10^{-1}$ meters per second (m/s), respectively. In terms of time, this means that the 0.1, 1.0, 10, and 100 μm particles require 315 hours, 7.5 hours, 5 minutes, and 4 seconds to settle 1 meter in perfectly calm air, respectively. This means that for particles smaller than about 10 μm (PM10) a light breeze can keep the particle from settling. While PM2.5 particulates such as photochemical smog (mostly nitrogen particles), smokes, and fine dust essentially do not settle from the atmosphere, but are kept aloft by Brownian motion and wind currents [4]. For these particles, gravity is not an effective removal mechanisms, but they are removed from the atmosphere by contact with a surface or by washout from precipitation. Contact can either by a dry surface where static charges capture the particle, or wet surfaces. Static surfaces soon fill, and subsequent particles either are not captured or displace an existing particle which is resuspended. Wet surfaces, such as Utah Lake, capture any of the fine particles that touch the surface.

PM2.5 and PM10

Particulate matter less than 10 μm (PM10) and particulate matter less than 2.5 μm (PM2.5) in diameter are monitored as indicators of air quality. Kuprov*, et al.* [5] studied atmospheric pollution in Utah and noted that Utah Valley, the location of Utah Lake, is a non-attainment area for PM_{10} and $PM_{2.5}$ which means that particulate levels are high for these particle sizes.

PM2.5 levels 98th percentile averaged across 18 air quality monitors throughout the Wasatch Front from 2004 to 2015 (https://health.utah.gov/utahair/pollutants/PM/) was between 40 and 50 μg/m³ while the 98th percentile for PM10 averaged about 10 μg/m³ over the same time period. The Wasatch front met the 1997 PM2.5 24-hour primary standard of 65 μg/m³. However, when this standard was lowered to 35 μg/m³ in 2006, the Wasatch Front were unable to comply and were re-designated as nonattainment with levels that exceeded that value. For PM10, Salt Lake and Utah Counties have been designated as nonattainment for the 24-hour primary standard of 150 μg/m³. In general, both areas have been in compliance with the national standards since 1996, but disagreements regarding the classification of exceedances due to windborne dust during high wind events have prevented re-designation to attainment or maintenance (https://health.utah.gov/utahair/pollutants/PM/).

The State of Utah (https://health.utah.gov/utahair/pollutants/PM/) estimates that over 30% of ***primary*** PM2.5 particle emissions in Utah came from dust in 2011. Fires contributed over 15%, while fuel combustion and mobile sources emitted 15% and 12.5% of the total ***primary*** PM2.5 particles, respectively. However, most PM2.5 is made of secondary particles, those formed in the atmosphere from other pollutants such as NOx as discussed above. Regarding PM10, the State says that in 2014, 67% of the primary PM10 particles in Utah came from dust, largely from unpaved roads with other sources including agriculture and industrial processes which contributed approximately 17% and 5%, respectively, of the total primary PM10 particles. There are also secondary PM10 particulates, but not as prevalent as secondary PM2.5 particles.

During a precipitation event, most of the particulate matter in the atmosphere, including PM10 and PM2.5, is washed-out or deposited with the precipitation. For discussion purposes, if we assume that the particulate pollution above Utah Lake extends 1,500 meters above the valley floor, about half way up the mountains, and we assume that the concentration is 10 μg/m³ (the approximate average from 2004 to 2015) there would be 15 mg/m² of PM2.5 AD for each precipitation event if the event washed out all the particulates. For PM10, assuming 150 μg/m³, (the non-attainment value), AD would be 225 mg/m² per precipitation event.

Atmospheric Deposition Mechanisms

For this discussion we classify atmospheric deposition (AD) into three different processes: settlement (dust), contact, and washout. Settlement occurs when large particles, 10 – 100 μm leave the atmosphere due to gravity. They settle on the ground and are only resuspended by a strong wind or mechanical action. Contact refers to smaller particles, less than 10 μm, and especially less than 2.5 μm, which leave the atmosphere when they contact a surface and "stick" because of electrostatic charge or moisture. These particles do not settle, and surfaces soon become "saturated" so that additional particles either are not captured or displace an existing particle. These smaller particles can settle slightly, but they are easily resuspended if they are not attached to a surface. Washout refers to particles that are washed out of the atmosphere during a precipitation event. This includes dust (> 10 μm), fines (< 10 μm), and gases. For all three processes, if the particles come in contact with the Utah Lake surface, they are captured and not resuspended, they stick when they contact the water surface.

Using this classification, we can describe nutrient AD using the following equation:

$$AD_{total} = AD_{dust} + AD_{contact} + AD_{precip} \quad \text{Eq 1}$$

Where AD_{total} is the total nutrient AD on Utah Lake, AD_{dust} is the nutrient AD from settleable dust, $AD_{contact}$ is the nutrient AD from fine particles less than 10 μm that are deposited by contact with the water surface, and AD_{precip} is the nutrient AD from materials washed out of the atmosphere from a precipitation event.

Utah Lake Nutrient AD Studies and Measurements

AD Studies

We have results from at least four separate studies of nutrient AD on Utah Lake, each focusing on a different type of deposition, settlement (AD_{dust}), total (AD_{total}), or washout (AD_{precip}). Some of these studies collected measurements designed to quantify AD on Utah Lake, others use data from literature studies to estimate AD rates, including literature studies from Utah locations, but not near Utah Lake. While all these studies also report on nitrogen loads, for discussion here we will only consider phosphorous. Nitrogen loads are similar, with the exception that gas solution from the atmosphere to the lake or into precipitation also occurs.

Dr. Janice Brahney performed an in-depth literature review of dust deposition in Utah and elsewhere in the Great Basin [1]. This work summarizes current knowledge on total and soluble phosphorus loading from dusts and summarizes atmospheric deposition rates of nitrogen from wet, gaseous, and particulate sources as reported in the literature. This includes urban depositions, both on the Wasatch Front and other locations, and deposition in the mountains and summarizes 7 different Utah dust measurements reported in two different studies (see Table 2 in [1]). Brahney [1] generates estimates of total (urban + regional) nutrient loading to Utah Lake based on these literature values and found that 80% of estimates fell between 2 and 9 metric tons of Total Phosphorus (TP) deposition to Utah Lake per year, with estimates of the bioavailable fraction at a minimum of 0.5 to a maximum of 7.9 metric tons, with probable deposition rates between 2 to 2.5 metric tons per year. Brahney [1] states that the study does not consider wet deposition. The Utah studies (Table 2 in [1]) all use the bulk marble collection method which generally captures dust, but not smaller particles such as PM10 or PM2.5. While some small portion of these fine particles are captured, many are resuspended or not captured at all because they do not settle onto the collector. Brahney [1] reports TP dust concentrations as deposition rates, rather than as mass concentrations in the dust. It is not clear how dust mass measurements from Table 2 were converted to TP deposition rates. It appears that phosphorous concentrations and deposition rates from other studies were used to estimate TP rates, rather than data from the Utah sites, though this is unclear. This study mostly measures dust (AD_{dust}) though some fines are captured.

Dr. Greg Carling (personal communication with Theron Miller) measured AD at four locations along the Wasatch front at university campuses in Provo, Salt Lake, Ogden, and Logan using the bulk marble method. He measured phosphorous concentrations in the dust and estimated that ~55 tons/year of TP is deposited on Utah Lake. The closest measurement in this case was at the BYU campus in an urban area surrounded by lawns and pavement about 300 meters, or more, above the Utah Lake surface and away from dust storms on the valley floor. Again, the bulk marble method mainly measures dust (gravity) AD, and not contact or precipitation AD. This study mostly measures dust (AD_{dust}) AD, though some fines are captured.

Dr. Woodruff Miller has collected rainfall at 9 locations around Utah Lake for the past 6 years amounting to a total of 850 samples. These samples were collected close to the lake, away from any local dust source. He collects the precipitation samples shortly after a rainfall event and sends the water to a certified laboratory for analysis. The laboratory measures and reports concentration of TP in mg/L. Dr. Miller uses the precipitation gage at the Utah Lake outfall to determine the amount of precipitation that falls over the lake surface. His previous reports used an average TP concentration along with the precipitation among and the area of Utah Lake on that date, to compute the amount of TP deposited to the Lake. His estimates range from 88 - 142 tons/year of TP. A more recent analysis (not yet published) uses 7 rain gages around the lake along with geostatistics to compute rainfall intensity maps with the same methods used with data from the 9 sample sites to compute concentration maps across the lake for each precipitation event. These maps are then combined with the lake area to estimate deposition for each event. Preliminary results from this study are similar to those reported by Miller. These studies focus on measuring AD from precipitation. While some dust or fines were captured by the rain gages, these gages were not designed to capture or retain the dust or fines, so we

expect these contributions are minimal. This study mostly measures precipitation (AD_{precip}) AD, though some dust is captured.

The final study, reported by Barrus, et al. [2], uses buckets to capture all the settlement (AD_{dust}), contact ($AD_{contact}$), and washout (AD_{precip}) AD [2,6]. This study uses an open bucket filled with deionized water to capture contact and dust AD and a separate bucket to capture precipitation AD. However, for much of the time, the mechanism that was used to switch the buckets did not work, so the total of all three AD processes was reported. This study collected 336 measurements in locations near Utah Lake. For these studies, both the concentration and volume of water in the buckets were measured and converted to mass (mg) of TP per area per sample period (typically one week, though occasionally longer).

The first study [6], was provided to the Utah Lake Science panel and they had concerns about collection height, location of solar panels related to the buckets, potential splash from bucket lids, and insects in the collections. In the subsequent study, [2], these issues were all addressed with side-by-side collections or other approaches. While collection methods were changed, (buckets raised to 2 m, solar panels moved, and miner's moss placed on bucket lids), statistically these were shown to be no different from the initial collections. The addition of screens on the buckets to exclude insects did have an impact on some sites, but not others.

This subsequent study compared the data from all the collection sites and found that the data from any given site, with the exception of Saratoga Springs, were not statistically different from any other site. This included the site at Bird Island. In other words, the stations were all measuring the same process. Since the measurements at Bird Island, were not statistically different than shoreline measurements, this indicates that there is little to no attenuation in AD rates. Barrus, et al. [2] estimated total TP loads of 262 and 133 tons/year for unscreened and screened samplers, respectively.

Supporting Study

An upcoming report from Telfer et al (2023 – not yet submitted), attempts to determine the source for dust in the samples around Utah Lake using samples from the on-going study reported by [2,6]. As part of this study, laboratory analysis requires at least 0.1 grams of solids. To acquire the dust samples for analysis, Telfer filtered the samples that had been archived from the 5.5 month summer period from the 2022 sample year. These samples were not meant to measure dust, and not all the samples were retained, though the majority were available. Telfer needed filter all the samples to obtain enough dust for analysis. Telfer found that over the 5.5 months fall and spring periods the study, he collected the amounts of dust shown in Table 1.

Table 1 Dust collected over spring and fall 5.5-month periods.

Location	**Dust Collection (grams)**
Mosida (fall)	0.05
Mosida (spring)	0.07
Lake Shore (fall)	0.11
Lake Shore (spring)	0.11
Pump Station (fall)	0.03
Pump Station (spring)	0.16
Orem (fall)	0.05
Orem (spring)	.0.07
Bird Island (total)	0.05
Bird Island (total - minus last sample)	0.02

This study was done during the high dust production period for the area.

Bird Island results are interesting. There was so little dust in the samples, that they could not be split into spring and fall intervals, but the entire sample set was filtered to obtain 0.05 grams of dust. Also of interest, the last sample contained 0.03 grams of that total, while the remaining 10 months contained only 0.02 grams. One large dust storm deposited more than half the total dust over the 11 month period on Bird Island. If the last sample collected is ignored, the Bird Island sampler only collected one fifth the dust compared to Mosida and even less compared to the other samplers. This episodic nature of dust deposition is consistent with Brahney [1] who notes that over 15 years of dust-on-snow measurements, some years had as few as 3 events per year, while others have up to 12. While filtering the samples, Telfer noted that there were samples from Bird Island containing zero or near zero measurable dust for several of the weeks. Bird Islands proximity to West Mountain may protect it from some winds, creating the reduced dust deposition.

These Bird Island data indicates that there is attenuation in dust AD over Utah lake (large, settleable particles) even though the nutrient AD data from [2] indicated no attenuation.

To collect the dust, Telfer filtered the sample water from the buckets using a 0.45 μm filter. In the Telfer study, each bucket has an area of 0.041 m^2, so deposition rates for the minimum and maximum samples of 0.04 and 0.11 grams results over 5.5 month periods range from 0.98 g/m^2 to 2.68 g/m^2, respectively. These correspond to annual rates of 2.14 and 5.85 $g/m^2/yr$, respectively.

This study and these samplers were not designed to capture dust. A few samples were missing, the samplers were not designed to measure dust, and any soluble particles, such as NOx salts or organics, would have dissolved. Several of the samples collected for the study contained algae, which plugged the filters quickly and were therefore discarded. This also reduced the amount of dust collected. Brahney reported a Utah Urban average of 24.7-56.7 $g/m^2/yr$ which is higher than these values, but a similar order of magnitude. We know that the majority of PM10 and PM2.5 are soluble nitrogen salts, so these values are reasonable.

Discussion

These four separate studies measure different AD processes, settlement (AD_{dust}), contact ($AD_{contact}$), washout (AD_{precip}) and (AD_{total}). Brahney and Carling measure dust (AD_{dust}) with some fines, Miller measures precipitation (AD_{precip}) with some dust, while Olsen and Barrus measure (AD_{total}), or all three processes.

Table 2 AD study summary

Study	Process	Amount (TP tons/yr)	Notes	Number of Samples
Brahney	dust	2 – 9	Includes some minimal contact	Varies
Carling	dust	55	Include some minimal contact	4
Miller	precipitation	88 - 142	Includes some minimal dust and contact	850
Barrus	contact, dust, precipitation	133 - 262	The lower value is screened	306

Using these studies, we can estimate contributions from the different processes. For example, if we assume that AD_{dust} = 2 tons/yr, AD_{precip} = 88 tons, and AD_{total} = 133 tons/yr, then $AD_{contact}$ = 43 tons/yr. Using these assumptions, then AD_{dust}, AD_{precip}, and $AD_{contact}$ contribute 1.5%, 66%, and 32% of the AD, respectively. If we assume that AD_{dust} = 9 tons/yr, then $AD_{contact}$ would be 36 tons/yr with percentages of 6.8%, 66%, and 27% for dust, precipitation, and contact processes, respectively.

This shows that these studies do not contradict each other, but rather support each other. The low percentage of AD from dust, shows that the attenuation demonstrated by the Bird Island dust samples is less than the variance in the data, demonstrating why the total AD measurements at Bird Island are not statistically different from the measurements at the other sample sites.

While $AD_{contact}$ estimates of 36 to 43 tons/yr are high, recall that Utah Valley suffers from high PM2.5 and PM10 levels, so contact deposition in this range is reasonable.

We would also like to stress that only the Miller, Olsen, and Barrus studies measured conditions near the lake, both the Brahney and Carling studies measured deposition significant distances from the lake under different conditions. The Utah campuses (BYU, UofU, Weber, and USU) are all elevated and located in urban green areas with few large dry dust sources. In the summer you can see the haze in the valley from these campuses and they are above a good part of it.

In addition, Brahney lowers AD estimates based on estimated attenuation over the lake. For dust (large gravity settling particles) this is correct and supported by the Bird Island data. But for smaller particles, attenuation is minimal and the data measured by both Miller and Barrus show no evidence of attenuation. The attenuation of the dust AD is within the variance of the data.

Conclusion

The Utah Lake AD studies initial appear to contradict each other because of the wide range of AD estimates. However, when considering that AD is driven by different processes, contact, dust (settlement), and precipitation, and that each study mostly measured only a subset of the total, it is clear that the studies are not contradictory, but rather complement and strengthen each other.

Based on this analysis, we conclude that an annual AD TP loading of rate of 250 tons/yr to Utah Lake is accurate. However, in consideration of the range of findings and potential implications, we propose 150 tons TP/yr could be used as a consensus-based value for evaluation.

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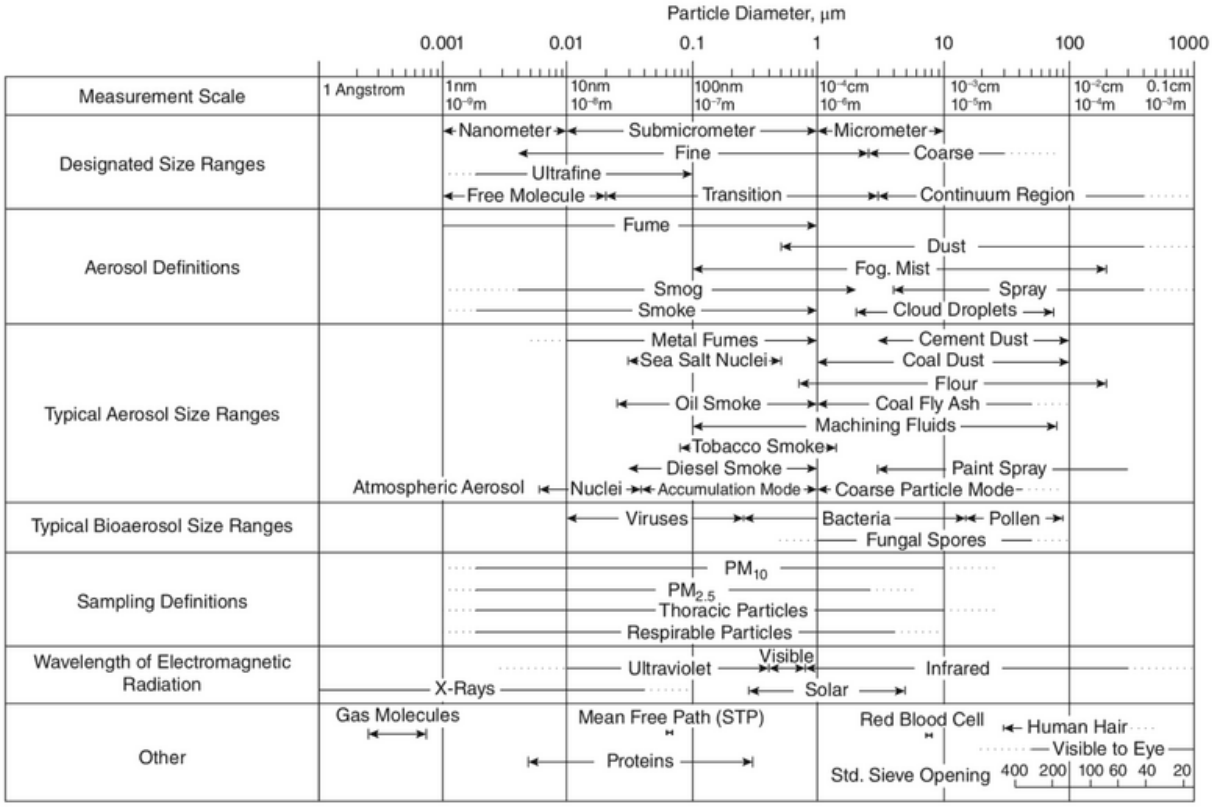
Appendix

From Atkinson [3]



1.6 Particle size ranges and definitions for aerosols.

Table 3.1 Effect of Pressure on Terminal Settling Velocity of Standard Density Spheres at 293 K [20°C].

Particle Diameter (μm)	V_{TS} at the Indicated Pressure (m/s)		
	$P = 0.1$ atm	$P = 1.0$ atm	$P = 10$ atm
0.001	6.9×10^{-8}	6.9×10^{-9}	6.9×10^{-10}
0.01	6.9×10^{-7}	7.0×10^{-8}	8.7×10^{-9}
0.1	7.0×10^{-6}	8.8×10^{-7}	3.5×10^{-7}
1	8.8×10^{-5}	3.5×10^{-5}	3.1×10^{-5}
10	0.0035	0.0031	0.0029
100	0.29	0.25	0.17

Table 3.1 Effect of Pressure on Terminal Settling Velocity of Standard Density

Table 1.2 Examples of Mass Concentration Expressed in Parts per Million[a].

	Mass Concentration, Mass/Volume (mg/m³)	Parts per Million, Volume/Volume (ppm)	Parts per Million, Mass/Mass (ppm)
U.S. $PM_{2.5}$ annual standard	0.012	1.2×10^{-5}	9.6×10^{-3}
Threshold limit value for nuisance dusts			
(Particulates not otherwise classified)	10	0.01	8
Uncontrolled stack effluent (typical)	10,000	10	8,000

a) Standard-density spheres.

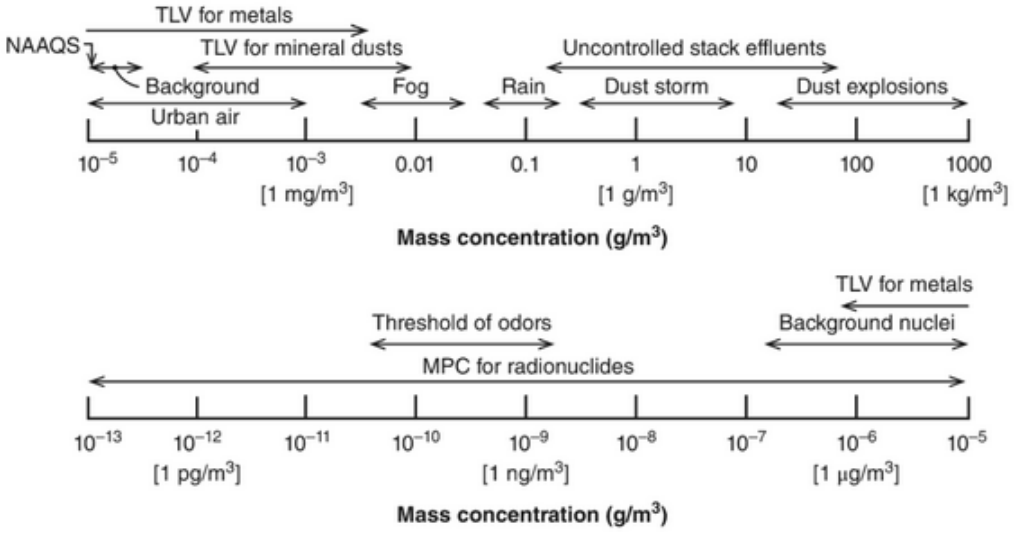


Figure 1.7 Range of aerosol concentrations (NAAQS=National Ambient Air Quality Standards, TLV=Threshold Limit Values, MPC=Maximum Permissible Concentration).

2/18/2023

Comments by David Gay

Dr. G. Williams, "Atmospheric Deposition of Nutrients to Utah Lake: Process and Research Overview" and Dr. Theron Miller email.

Complementary nature of the different samples: I agree with Dr. Williams on this conclusion of complementariness. The different measurements are complementary to the total Atmospheric Deposition (AD_{total}). The studies mentioned all measured a part of the AD_{total} equation, and not the total deposition (except Barrus). This is driven in part by the difficulty, cost, assumptions made, and disagreements of how to make dry deposition measurements. Dry deposition measurements can be made, but are fraught with error, inconsistencies, and assumptions. As Dr. Williams suggests, you need to compare like to like measurements, realizing that they are all part of the total deposition equation. Additionally as he suggests, a bulk measurement of wet deposition (without a closing top), will generally accurately measure wet deposition, but the concentrations are likely biased high by added dry deposition (AD_{dust}, $AD_{contact}$).

I will go one step further and suggest, based on the above, that the wet deposition collections made with closing samplers are likely the best measurements (true AD_{precip}) as compared to the dry deposition measurements (AD_{dust}, $AD_{contact}$) because they are easier measurements with fewer assumptions. Therefore I maintain that true AD_{precip} measurements can provide the basic deposition or minimum deposition to the lake, and that the dry deposition should be added to these measurements with the associated inaccuracies, errors and assumptions.

Going further out on a limb and following from the idea that this paper focuses on TP, I would argue that in Equation 1:

$$AD_{total} = AD_{dust} + AD_{contact} + AD_{precip}$$

The AD_{dust} and AD_{precip} are the most important components for the total lake deposition. Phosphorus does not have gaseous compounds, therefore gaseous particle formation of small particles is less likely to occur, so $PM_{2.5}$ and smaller sized particles with phosphorus compounds should be less important. Therefore, the more important category of TP deposition would primarily be AD_{dust}, and AD_{precip}.

Another Calculation

Table 2 AD study summary

Study	Process	Amount (TP tons/yr)	DG Notes
Brahney	dust	2 – 9	Dry only, literature study only
Carling	dust	55	Dry only, few measurements
Miller	precipitation	88 - 142	Wet plus some dry contam.
Barrus	contact, dust, precipitation	133 - 262	Wet plus dry measurement, but with problems

This is Dr. Williams table, but with the deposition description added in the final column. I don't know (or remember) the conditions surrounding the Barrus measurement problems mentioned by Dr. Williams. However, let's just assume that they are close to correct. And, if you add the Carling dry P measurements to the Miller wet P measurements, you get about the same range as the Barrus total P measurements. I think Brahney estimates are pretty low versus everything else I have seen. Carling measurements are only a few number and have the normal dry deposition measurement problems. Miller's wet deposition measurements have some problems too (not closed after precip, not a dry deposition sampler, etc.), but there are a lot of measurements. I have mentioned I don't know what Dr. Williams means with the problems for Barrus. But this summation of Carling + Miller estimates a range of about 140 to 200 for total P deposition. That is about the same range as Barrus. So with three independent studies, you arrive at about the same answer. This all suggests the 150 to 250 range noted by Dr. Williams is reasonable.

Another Calculation

Here is another way to get to the reasonableness of all of this.

The US EPA estimates total (wet and dry) deposition of N through modeling. See this location for the maps: https://nadp.slh.wisc.edu/committees/tdep/ with individual map links below at this site. Unfortunately they have not tried to model TP yet. However, my idea is this.

I calculated (see excel sheets) what total N deposition was for Utah Lake based on these modeling estimates for 2021. I get the following:

Using the total N deposition maps from EPA, for 2021					
	kg N per hectare		hecatres of lake	total N in tons (as N)	assume it is all as nitrate
TN dep	10		38,436	384	1,747

These are big numbers. My idea is to do the following.

- Compare the 384 tons of deposition as N (or 1747 tons as NO3) versus the Utah Board's preferred number for atmospheric N deposition. Does it compare well?

- If EPA> Utah Board, this is another qualified estimate of N deposition to Utah Lake that says the Utah Board values are too low.
- If you have data that says the mass ratio of N to P in your samples is X, then you can estimate TP deposition from the EPA TN deposition values.
- Then if this estimate of TP is much greater than the Utah Board estimate, then you have a logical estimate to argue that the TP values they want to use are also probably low.
- For example, if wet and dry deposition measurements say that there is 1 atom/molecule of P for every 10 atoms/molecules of N, then this would argue that the total deposition of P to the lake is 384 tons N * 0.10 = 38.4 ton P.
- This is something of a stretch, but it is somewhat reasonable.

Based on my calculations and other observations, it seems that a 40-50% estimate of 50 TP: 100N is about right. Brahney's values are very, very low and are only for dry deposition. The same is true for Carling. Miller is only for wet deposition plus some dry. Barrus's are actually for total deposition, and range from 0.43 to 1.70 P:N. If you just assume the low end of this (40-50%), then you get an estimate of total deposition to the lake.

If you multiply this by the EPA estimate of Total N deposition (wet and dry), you come in at about 150 to 195 tons P per year to the Lake (both wet and modeled dry deposition estimates). This makes Dr. William's estimate of 150 or 250 about right; it strikes me as at least reasonable, based on others data.

Again, there might be better estimates of the ratio of P to N, which could be used.

Other Matters

Also, I have noted before, that insects into the lake may not officially be considered "wet deposition" by anyone. We don't with NADP. But for the TN and TP load, it would seem to me that this could be a significant source of both to the lake, and should be considered in the TN/TP load estimates and calculations.

Opinion on the "stickyness" of a water surface. Basically, I agree with your opinion, Theron. Almost any particle coming in contact with a free water surface is essentially going to get stuck to the water through chemical charge interaction, or if it is heavy enough it will sink into the water. And, it seems to me that no particle is going to leave the fluid on its own. A lake, with waves and wind is going to generate water aerosols certainly that could carry suspended particles with them back into the atmosphere. But the idea that the lake is a somewhat passive collectors of atmospheric particles is correct. Any particle with a significant deposition velocity and quiet atmospheric conditions will pick up particles from the atmosphere, whether they are

anthropogenic or naturally occurring. Therefore, this should be occurring with Provo/Salt Lake urban smog into Utah Lake. Larger particles of 10 microns and above will settle out fairly quickly, and as dust plumes move over the lake, I would certainly expect the larger dust particles to settle into the water and the dust cloud would become less and less concentrated as it moves across the lake. I would expect significant attenuation of large particles by the time you reach Bird Island and the east side of the lake.

How significant is this? That is a very good question. It would depend upon the atmospheric concentrations, the size of the particles (likely very small, fine fraction), and the atmospheric conditions. Higher concentrations, larger particles, and more quiet atmospheric conditions will increase this deposition, and vice versa.

This phenomena is essentially dry deposition but to a liquid surface.

I do not understand why Dr. Williams concludes "we recommend a annual TP loading of 150 tons/yr (rounded), though we feel that a rate of 250 tons/yr is more accurate.". I would think he would recommend 250 tons TP to the lake.

Additionally, I have included comments to the document, as you will see below. Some of these you might find useful. Most of what Dr. Williams says in his report I agree with, as you will see in my comments. However, it comes down to who's measurements or calculations for dry deposition that you believe. It is very, very difficult to measure, and is always controversial.

D. A. Gay

Filename: Effects of screens on AD of TP in samplers

November 3, 2022

Screen Effects on TP in AD samplers

Technical Memo

To
Wasatch Front Water Quality Council
Salt Lake City, UT

By
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Justification

There is much concern by DWQ Utah Lake Science Panel (ULSP) on the amount of nutrients accumulating on Utah Lake from atmospheric deposition (AD). Presently, the ULSP is considering using only screened sampler data from Barrus et al. (2020) raw data after removal of insect or debris contaminated samples to calculate AD loads. However, Barrus et al. (2021) and Richards (2020) reported that screened samplers significantly reduced TP deposition. Accurate estimates of AD of nutrients will not be possible if the effects of screens on AD are not accounted for. This cursory analysis addresses this concern.

Methods

Raw data from Seth Barrus Excel file titled, "AD_Results_Barrus", sheet name: "CombinedStats per m2" were analyzed. Table II on that sheet provided 48 sampler data from Central Davis High and Orem paired screened and unscreened (NADP) samplers (Table 1).

Table 1. ***II.*** *Comparison between NADP and SDSD Sample Tables (No filter - NADP, Filter - SDSD): Total Phosphorus (mg/m2) from Barrus 2020 Excel spreadsheet.*

Date	Central Davis High	Central Davis NADP	Orem	Orem NADP
6/25/20	1.9736	4.4820	2.0095	22.9642
7/2/20	2.6770	3.0465	2.6660	7.0593

7/10/20	0.8675	3.3352	0.6988	9.4431
7/17/20	N/A	N/A	2.4678	5.4925
7/23/20	2.7951	N/A	4.9859	4.5119
7/30/20	N/A	N/A	0.9500	23.7307
8/10/20	2.4922	6.2892	1.0434	66.5338
8/21/20	5.0232	7.9270	2.3631	232.5352
8/28/20	42.2723	41.6804	3.5383	49.7937
9/4/20	N/A	N/A	2.4220	5.2501
9/11/20	N/A	5.6627	59.9064	83.9371
9/18/20	19.0458	4.0492	1.2663	4.2267
9/25/20	2.1758	3.3842	2.1909	4.0811
10/2/20	2.9420	4.3022	1.6954	8.2823
10/9/20	1.0739	3.6930	2.1695	3.4091
10/15/20	4.0970	4.0859	2.5183	3.6299
10/23/20	1.7816	11.1853	1.2217	3.7653
10/29/20	1.5314	4.7025	34.4981	1.6064
11/12/20	N/A	N/A	23.8514	42.5714
11/19/20	N/A	N/A	3.1592	5.3603
11/25/20	7.1850	15.9369	1.5063	10.5526
12/3/20	6.9812	1.1643	2.3049	8.6842
12/10/20	0.9690	0.6500	1.5589	2.5119
12/16/20	1.2232	1.8235	1.2048	4.3610

The following table (Table 2) is reordered with Bug/Debris added from Barrus 2020 sheet name: "Overall".

Table 2. Reordered Table 1 with bug/debris samples added from sheet "Overall" Barrus spreadsheet.

Date	Screened	Unscreened	Location	Bugs/Debris
8/21/20	5.0232	7.9270	**Central Davis High**	3
10/23/20	1.7816	11.1853	**Central Davis High**	7
10/23/20	1.2217	3.7653	**Orem**	13
8/21/20	2.3631	232.5352	**Orem**	50
11/12/20	23.8514	42.5714	**Orem**	debris
10/15/20	4.0970	4.0859	**Central Davis High**	y
10/15/20	2.5183	3.6299	**Orem**	y
10/29/20	1.5314	4.7025	**Central Davis High**	y debris
6/25/20	1.9736	4.4820	**Central Davis High**	
7/2/20	2.6770	3.0465	**Central Davis High**	
7/10/20	0.8675	3.3352	**Central Davis High**	

7/17/20	N/A	N/A	**Central Davis High**
7/23/20	2.7951	N/A	**Central Davis High**
7/30/20	N/A	N/A	**Central Davis High**
8/10/20	2.4922	6.2892	**Central Davis High**
8/28/20	15.9369	41.6804	**Central Davis High**
9/4/20	N/A	N/A	**Central Davis High**
9/11/20	N/A	5.6627	**Central Davis High**
9/18/20	19.0458	4.0492	**Central Davis High**
9/25/20	2.1758	3.3842	**Central Davis High**
10/2/20	2.9420	4.3022	**Central Davis High**
10/9/20	1.0739	3.6930	**Central Davis High**
11/12/20	N/A	N/A	**Central Davis High**
11/19/20	N/A	N/A	**Central Davis High**
11/25/20	7.1850	15.9369	**Central Davis High**
12/3/20	6.9812	1.1643	**Central Davis High**
12/10/20	4.5119	0.6500	**Central Davis High**
12/16/20	23.7307	1.8235	**Central Davis High**
6/25/20	2.0095	22.9642	**Orem**
7/2/20	2.6660	7.0593	**Orem**
7/10/20	0.6988	9.4431	**Orem**
7/17/20	2.4678	5.4925	**Orem**
7/23/20	4.9859	4.5119	**Orem**
7/30/20	0.9500	23.7307	**Orem**
8/10/20	1.0434	66.5338	**Orem**
8/28/20	3.5383	49.7937	**Orem**
9/4/20	2.4220	5.2501	**Orem**
9/11/20	59.9064	83.9371	**Orem**
9/18/20	1.2663	4.2267	**Orem**
9/25/20	2.1909	4.0811	**Orem**
10/2/20	1.6954	8.2823	**Orem**
10/9/20	2.1695	3.4091	**Orem**
10/29/20	34.4981	1.6064	**Orem**
11/19/20	3.1592	5.3603	**Orem**
11/25/20	1.5063	10.5526	**Orem**
12/3/20	2.3049	8.6842	**Orem**

12/10/20	1.5589	2.5119	**Orem**
12/16/20	1.2048	4.3610	**Orem**

There were eight bug/debris 'contaminated' samples that I removed from further analysis. I then calculated Difference = unscreened – screened and descriptive statistics.

Results

The difference between paired screened and unscreened data was calculated (Table 3).

Table 3. Difference between screened and unscreened TP concentrations mg/m2.

date	screened	unscreened	site	Difference
6/25/20	1.9736	4.482	Central Davis High	2.51
7/2/20	2.677	3.0465	Central Davis High	0.37
7/10/20	0.8675	3.3352	Central Davis High	2.47
7/17/20	0.05	0.05	Central Davis High	0.00
7/23/20	2.7951	0.05	Central Davis High	-2.75
7/30/20	0.05	0.05	Central Davis High	0.00
8/10/20	2.4922	6.2892	Central Davis High	3.80
8/28/20	4.9859	41.6804	Central Davis High	36.69
9/4/20	0.05	0.05	Central Davis High	0.00
9/11/20	0.05	5.6627	Central Davis High	5.61
9/18/20	19.0458	4.0492	Central Davis High	-15.00
9/25/20	2.1758	3.3842	Central Davis High	1.21
10/2/20	2.942	4.3022	Central Davis High	1.36
10/9/20	1.0739	3.693	Central Davis High	2.62
11/12/20	0.05	0.05	Central Davis High	0.00
11/19/20	0.05	0.05	Central Davis High	0.00
11/25/20	7.185	15.9369	Central Davis High	8.75
12/3/20	6.9812	1.1643	Central Davis High	-5.82
12/10/20	3.5383	0.65	Central Davis High	-2.89
12/16/20	0.05	1.8235	Central Davis High	1.77
6/25/20	2.0095	22.9642	Orem	20.95
7/2/20	2.666	7.0593	Orem	4.39
7/10/20	0.6988	9.4431	Orem	8.74
7/17/20	2.4678	5.4925	Orem	3.02
7/23/20	4.9859	4.5119	Orem	-0.47
7/30/20	0.95	23.7307	Orem	22.78

8/10/20	1.0434	66.5338	Orem	65.49
8/28/20	3.5383	49.7937	Orem	46.26
9/4/20	2.422	5.2501	Orem	2.83
9/11/20	59.9064	83.9371	Orem	24.03
9/18/20	1.2663	4.2267	Orem	2.96
9/25/20	2.1909	4.0811	Orem	1.89
10/2/20	1.6954	8.2823	Orem	6.59
10/9/20	2.1695	3.4091	Orem	1.24
10/29/20	34.4981	1.6064	Orem	-32.89
11/19/20	3.1592	5.3603	Orem	2.20
11/25/20	1.5063	10.5526	Orem	9.05
12/3/20	2.3049	8.6842	Orem	6.38
12/10/20	1.5589	2.5119	Orem	0.95
12/16/20	1.2048	4.361	Orem	3.16

The mean difference in TP (mg/m2) between screened and unscreened side by side paired samples was 6.02 mg/m2 and the proportion difference (mean unscreened/mean screened) was 2.26 mg/m2 from samples with bugs/debris removed (Table 4). This shows that screens had a very large effect on reducing the amount of AD that went into a sampler. Reasons are speculative, for example screens accumulated AD, wind blew AD off screens, etc.

Table 4. Descriptive statistics of screened and unscreened TP mg/m2/week.

stats	screened	unscre~d
mean	**4.78**	**10.8**
sd	**10.7**	**18.3**
p50	**2.17**	**4.33**
p25	**.997**	**2.17**
p75	**3.05**	**8.48**
max	**59.9**	**83.9**
min	**.05**	**.05**
range	**59.9**	**83.9**

stats	Difference
mean	6.01
sd	15.8
p50	2.49
p25	0
p75	6.48

max	65.5
min	-32.9
range	98.4

Conclusion

AD samplers with screens had a very significant negative effect on TP deposition measurements and can significantly bias AD nutrient load estimation on Utah Lake.

Recommendation

Do not use screened data only, because screens reduced TP by about 56%, which is consistent with Barrus et al. 2021 publication and my initial analyses, Richards 2020. I recommend using both screened and unscreened data after adjusting screened data to account for screen effect and after removing contaminated samples to estimate nutrient loads more accurately to Utah Lake from AD.

Literature Cited

Barrus, S. M. et al. 2021. Nutrient Atmospheric Deposition Sampling and Analysis Improvements: Utah Lake Impacts. Hydrology.

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