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First Episodic Atmospheric Deposition of Nutrients to Utah Lake: Statistical Analysis and Characterization

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Abstract

Atmospheric deposition (AD) is a significant but poorly understood source of nutrients to many aquatic systems around the world. Accurate characterization of the nutrient budgets of aquatic systems is critical to good management decisions, so a better understanding of AD-related nutrient loads is essential, especially for water bodies where nutrient loads from atmospheric deposition are significant. Due to its large surface area, proximity to Great Basin dust sources, high values of atmospheric particulates due to inversions, and the high phosphorus content of local soils, Utah Lake, in the semi-arid Utah Valley, USA, experiences significant phosphorus loading from AD. The lake is eutrophic and has a history of impaired water quality and HABs, which has motivated significant study and debate over nutrient loads to the lake. Previous studies that measured phosphorus AD to Utah Lake showed a large portion of the AD was associated with a few high-volume deposition events, with the data exhibiting unexpectedly high peaks at some locations on a few dates. These issues cast doubt on the data. We used statistical analyses and machine learning models to characterize AD to Utah Lake. In addition to determining the distribution of AD events, we analyzed the relationship between phosphorus AD and local weather events. We used this analysis to determine whether the high phosphorus measurements were outliers due to sampling errors or represented actual conditions. Our analysis shows that AD events followed an XXX distribution, similar to the distribution of precipitation events on the lake. We found the high phosphorus deposition events were correlated with instances of high wind occurring when the ground was dry. We also observed regular cycles of higher and lower measurements throughout the year that are like measures of atmospheric particulate matter. We conclude that atmospheric phosphorus deposition on Utah Lake is episodic and driven by weather conditions around the lake, with the most important factors being the number of hours with high winds during a collection period and the percentage of those hours where the ground was dry during a collection period followed by dry deposition from particulate matter. This is an important finding for the management of Utah Lake and also has implications for the management of other eutrophic lakes in which atmospheric deposition of nutrients impacts water quality.

Keywords: Atmospheric deposition, nutrients, episodic events

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Table of Contents

Table of Figures

List of Tables

1. Introduction

1.1 Water Quality and Atmospheric Deposition

Atmospheric deposition (AD) of nutrients can have a major impact on water quality. Most AD studies focus on dust deposition and longer-range transport of nutrients, bacteria, and other materials such as metals [1-3], but do not necessarily focus on water quality impacts. While there is considerable literature on AD of nutrients to oceans [4-7], there has been less published work on freshwater lakes and reservoirs. AD processes are an important part of nutrient cycling and should be considered in water quality management, especially in arid regions. As there are few studies on nutrient AD to freshwater lakes published in journals focusing on water and water quality, this study contributes to this literature, informs water managers and researchers, and provides tools to assess the impacts of AD processes.

While literature on AD to freshwater lakes is more limited than other areas, there is considerable work on the Great Lakes (e.g., [8, 9]), the Everglades (e.g., [10]), and Lake Tahoe [11, 12] in the United States and on other lakes worldwide in areas such as India [13-15], China [4, 16, 17], Africa [18, 19], and Europe and Asia [20], among others. However, these lakes differ from Utah Lake, as Utah Lake is uniquely situated in a dry urban area, subject to both dust storms from desert and agricultural areas and urban particulate matter due to proximity to urban areas and strong summer inversions.

Utah Lake, a remnant of Pleistocene Lake Bonneville, is a shallow eutrophic freshwater lake approximately 50 km (30 miles) long and 10 km (6 miles) wide [21] located in northern Utah. When full, the surface area of the lake is roughly 40,000 hectares (95,000 acres) with an average depth of 2.8 meters (9.2 feet) [21]. Due to its large surface-area-to-volume ratio, the lake is particularly susceptible to atmospheric deposition of nutrients [22]. The lake is considered highly eutrophic by the Larsen-Mercier Tropic State model and moderately eutrophic by the Carlson Trophic State Index model [21]. We have collected a unique data set with AD measurements over five years, mostly weekly during the non-winter months as 5 to 7 locations around the lake [23] that make this study possible.

1.2 Atmospheric Deposition of Phosphorus

1.2.1 Particulates in the Atmosphere

Phosphorus (P) is a principal macronutrient and a limiting nutrient in many aquatic ecosystems [24]. Long-range transport of fine dust, as well as local movement of larger primary biological aerosol particles, contributes significantly to P loading of water bodies around the world [4-7]. The AD contribution to nutrient loading is a poorly understood component of the nutrient budget for many water bodies [25]. This is largely due to the difficulty of measuring P deposited through AD compared with other P sources such as surface tributaries and storm and wastewater discharges, and the fact that both AD rates and the associated nutrient loads vary significantly with the physical characteristics of the water body, the surrounding landscape, and meteorological conditions [25].

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, for regulatory purposes in the United States it has been divided into two categories based on diameter. $PM_{2.5}$ are particles with a diameter smaller than 2.5 μm and are called fine particles. PM_{10} 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 the United States Environmental Protection Agency (EPA) [26].

This material in the atmosphere is 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 is noticeable as a brown haze during summer months. NOx reacts with other pollutants to form fine particulate matter in the atmosphere [27]. 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 compounds form particulates, with most of the nitrogen compounds present as the ammonium salts in particulate form, except for ammonium nitrite, which is a gas.

1.2.2 Atmospheric Particulate Settling

Particulates settle in the atmosphere based on their size and weight, with larger particulates settling faster than smaller particulates. For example, dust particles larger than 10 μm may settle within a few hours, while smaller particles, like $PM_{2.5}$, can stay in the atmosphere for days to weeks.

Hinds and Zhu [28] 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 8.8×10^{-7}, 3.7×10^{-5}, 3.1×10^{-3}, and 2.5×10^{-1} 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 m in perfectly calm air, respectively. This means that for particles smaller than about 10 μm (i.e., PM_{10}), a light breeze can keep the particle from settling. $PM_{2.5}$ particulates such as photochemical smog (mostly nitrogen particles with sorbed phosphorus), smokes, and fine dust essentially do not settle from the atmosphere, but are kept aloft by Brownian motion and wind currents [28]. For these particles, gravity is not an effective removal mechanism, rather they are removed from the atmosphere by contact with a surface or by washout from precipitation. Contact removal can occur either by contact with 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 contact the surface and do not fill, as the water surface is continually mixed.

Particulate matter less than 10 μm (i.e., PM_{10}) and particulate matter less than 2.5 μm (i.e., $PM_{2.5}$) in diameter are monitored as indicators of air quality. Kuprov, et al. [29] 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. Recorded data show that $PM_{2.5}$ levels in the 98th percentile averaged across 18 air quality monitors throughout the Wasatch Front (which represents the urban area where Utah Lake is located) from 2004 to 2015 were between 40 and 50 μg/m^3 while the 98th percentile for PM_{10} averaged about 10 μg/m^3 over the same time period [26]. Utah County met the 1997 $PM_{2.5}$ 24-hour primary standard of 65 μg/m^3. However, when this standard was lowered to 35 μg/m^3 in 2006, Utah County was designated as nonattainment, and for PM_{10}, Utah County has been designated as nonattainment for the 24-hour primary standard of 150 μg/m³. In general, Utah County has been in compliance with the national standards since 1996, but issues regarding the classification of exceedances due to windborne dust during high wind events have prevented re-designation to attainment or maintenance [26].

The State of Utah [26] 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 they are not as prevalent as secondary PM2.5 particles.

1.2.3 Types of atmospheric deposition

For discussion in this paper, we classify AD to water into three different processes: settlement (dust), contact, and washout. We define these processes as follows:

1. Settlement occurs when large particles (10 – 100 μm), which are transported by strong wind and other disturbances, leave the atmosphere due to gravity. They settle on the ground and are only resuspended by wind or mechanical action.
2. Contact refers to smaller particles, less than 10 μm, and especially less than 2.5 μm, experiencing Brownian motion, which leave the atmosphere when they contact a surface and "stick" because of electrostatic charge or moisture. These particles do not generally settle, and dry 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. When these particles contact a wet surface, such as a lake, they are captured.
3. 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 contact Utah Lake, they are captured and not resuspended.

When estimating total loads of AD-related P to a water body using the results of an observational study, it is essential to consider which of these categories was measured by the collection methods used in the study and which category might be the dominant AD pathway for that waterbody.

1.2.4 Episodic nature of phosphorus deposition

Studies of AD nutrient loads to marine and freshwater ecosystems have documented the highly episodic nature of deposition [30, 31]; in some cases, the majority of the annual load is deposited in just a handful of isolated events [32-34]. Since the key environmental processes that drive AD, such as precipitation and wind gusts, are episodic, it is not surprising that deposition has a similar pattern. A study in the everglades found that annual rates were dominated by episodic inputs associated with high winds rather than background deposition rates during fair weather [35], and a 2011 review of atmospheric deposition data on the Laurentian Great Lakes found that intense storm events can increase atmospheric phosphorus input into regional lakes but suggested that further research is necessary in order to understand the impacts of meteorological events on nutrient deposition to water bodies [25].

Not all deposition events affect nutrient loads in the same way, as this depends on the makeup of the dust being deposited. Factors such as upwind land use, soil type, soil moisture condition, and wind speed and direction impact the amount of P that enters a waterbody during an AD event [34]. Because of this, there is not necessarily a strong correlation between the amount of dust deposited and the total nutrient load deposited across various events—a large nutrient load can come from a single event, while a later event that deposits a similar amount of dust may not deliver the same amount of nutrients [34, 36].

For example, during a precipitation event, most of this particulate matter in the atmosphere, such as PM_{10} and $PM_{2.5}$, is washed out or deposited with the precipitation. A large portion of the PM2.5 are nitrogen oxide gases, which can significantly increase the deposited load for an event. Near Utah Lake, small particulate matter is high. If we assume, for discussion purposes, that the particulate pollution above Utah Lake extends to 300 meters above the valley floor, which is the typical height of the inversion layer, and we assume that the concentration of $PM_{2.5}$ is 10 μg/m^3 (the approximate average from 2004 to 2015) there would be 3 mg/m^2 of $PM_{2.5}$ AD for each precipitation event if the event washed out all the particulates. For PM_{10}, assuming 150 μg/m^3, (the non-attainment value which is often exceeded), AD would be 45 mg/m^2 per precipitation event. These are mass estimates, rather than nutrient estimates.

1.3 Atmospheric deposition on Utah Lake

1.3.1 Lake characteristics

Utah Lake is the largest freshwater lake in Utah and a valuable natural resource. Located in the semi-arid Utah Valley, it is shallow, turbid, slightly saline, and eutrophic. Its shallow, well-oxygenated, high pH waters degrade and stabilize pollution and support abundant wildlife as part of a productive ecosystem. The lake provides a wide range of ecosystem services including ecological habitat, climate moderation, water storage, and recreation (e.g., boating, sailing, fishing, and hunting).

As is the case for most eutrophic lakes, Utah Lake periodically experiences large, intense algal blooms which can impair beneficial uses. There is also concern over human impacts to the lake due to the rapidly expanding population surrounding the lake and a history of pollution in the area. Significant efforts have been made to understand the lake's unique ecosystem and history, and to identify the best strategies for enhancing and preserving the lake's health and function.

A critical part of this effort is the creation of an accurate nutrient budget for the lake. AD nutrient loads are a key component of the nutrient budget, but unfortunately are one of the more difficult components to characterize. Utah Lake is uniquely susceptible to AD-related nutrient loading due to its high surface area to volume ratio, summer inversions with high levels of particulate matter in the atmosphere, its location at the bottom of a valley near canyons that channel wind with accompanying particulate loads, and large areas of nutrient-rich dust-generating lands surrounding it. Soils in the area have phosphorus concentrations on the order of 1,000 mg/kg, much of which is available to the water column [37-39].

1.3.2 Utah Lake AD Estimates and Data

Studies have shown that contact deposition can be a major contribution to nutrient AD [40], with contact deposition often the dominant AD method of P deposition [22, 40]. Tamatamah, et al. [40] found that 75% of P deposition in Lake Victoria occurred under dry conditions, mostly by contact.

Local soils around Utah Lake are rich in phosphate [37-39, 41, 42], with up to 50% of the P in soils surrounding the lake present as either water-soluble, loosely-bound, or aluminum/iron-bound. Up to 0.50 mg of P for every 1 g of soil deposited on the lake is potentially available for use by phytoplankton [43].

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 contact the Utah Lake surface, they are captured and not resuspended.

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

$$AD_{total} = AD_{dust} + AD_{contact} + AD_{precip} \qquad \text{Eq 1.1}$$

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.

There have been several studies that have either estimated or measured nutrient AD to Utah Lake including dust [36], washout or precipitation ([44]) and all three sources, i.e., contact, dust, and washout [22, 23].

Brahney [36] performed a literature review to estimate dust loads and typical nutrient concentrations to Utah Lake [4, 36, 45]. The studies summarized in the report collected data from over 250 locations around the world, and estimated phosphorus loads for each continent. Several of the sampling locations were in the mountainous western United States, in landscapes like those surrounding Utah Lake. Brahney [36] used these western US locations to estimate deposition rates between 15 and 38 mg m^{-2} yr^{-1} for Utah Lake. These studies reported generally focused on dust, or larger particles and did not necessarily include contact deposition or rainout. This was a literature study, with no measurements at Utah Lake.

Brown [44] collected about 100 rainfall samples at each of 9 locations, for about 900 totals samples, around the lake, measured nutrient concentrations in the water over a 6-year period and estimated Utah Lake loads based on the precipitation concentration and precipitation volume measured at 6 different meteorological stations around the lake over the 6-year study period. Brown [44] mostly measured precipitation AD, often called bulk deposition in the literature, though the collection system did capture some minimal contributions from the dust and contact AD factions. This study was based on precipitation concentration and precipitation measurements at locations around Utah Lake.

Olsen, et al. [22] reported weekly data that measured nutrient mass loads from all three sources; dust, contact, and washout over a 4-year period; this study was updated with improved methods and another 2 years of data by Barrus, et al. [23]. This later study, [23], included the data from the previous study with approximately 600 samples over the 6-year period. These data are the focus of this study and are described in detail below. This study was based on mass deposition measurements at various locations around Utah Lake.

These results from separate studies of nutrient AD on Utah Lake, each focus on a different type of deposition, settlement (AD_{dust}), contact (AD_{total}), or washout (AD_{precip}). Brahney [46] performed a literature review and estimated that AD_{dust} is in the range of 2 to 9 tons/yr. Brown [44] collected about 900 samples around Utah Lake and measured concentrations in rainwater and estimated AD_{precip} of 88 to 142 tons/yr. Barrus, et al. [23] evaluated 600 samples collected around Utah Lake and estimated that the total AD (AD_{total}) was between 133 to 262 tons/yr.

The Utah Lake AD studies initially appear to contradict each other because of the wide range of AD load estimates. However, since AD consists of different processes, contact, dust (settlement), and precipitation, and that the first two studies measured either dust deposition or deposition from precipitation, while the third measures all three factions, these data show the studies are not contradictory, but rather complement and strengthen each other. 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 values, AD from dust is 1.5% to 6.8% of the total nutrient AD.

Barrus, et al. [23] conclude that an annual AD TP loading of rate of 250 tons/yr to Utah Lake would be appropriate for models and planning, though they acknowledge that load could be significantly lower in the 150 tons TP/yr range if higher concentration samples are excluded.

1.4 Study Goals and Motivation

In 2018, the Utah Department of Environmental Quality, Division of Water Quality (Utah DWQ) established the Utah Lake Science Panel (ULSP) which consists of experts from around the United States in addition to local researchers [47]. The ULSP "… is charged with guiding the development of site-specific nitrogen and phosphorus criteria that are protective of the aquatic life, recreational, and agricultural uses of the lake. Specifically, the Science Panel will develop a scientifically-defensible approach for establishing criteria, recommend studies and guide research activities to fill knowledge gaps, review and interpret study results…" [47].

In reviewing the AD studies, the ULSP determined that the majority of the data from [23] and [44] should be excluded because of the number of values that were significantly higher than those in the literature review. As of this writing, the ULSP is considering total P deposition in the range of 30 to 50 tons/yr, significantly lower than either of the two studies which used measured data around the lake [23, 44]. They estimated this value by excluding high values from the measured data set based on variance from the mean and attribute this variance to sample contamination such as bugs and insects. The impact of bugs and other sample contaminants is discussed in detail Barrus, et al. [23]. Brown [44] does not discuss contamination, though their sampling method is less prone to contaminated samples.

The motivation for this study is to evaluate the data from [23], which measures all three AD factions, to determine whether the higher deposition values should be excluded from the AD load estimates, or if these values are consistent with the expected statistical distributions and physical processes as we understand them. Our results will have a significant impact on Utah Lake management decisions, as the nutrient loads from different sources help determine which management and mitigation strategies are feasible and likely to impact water quality.

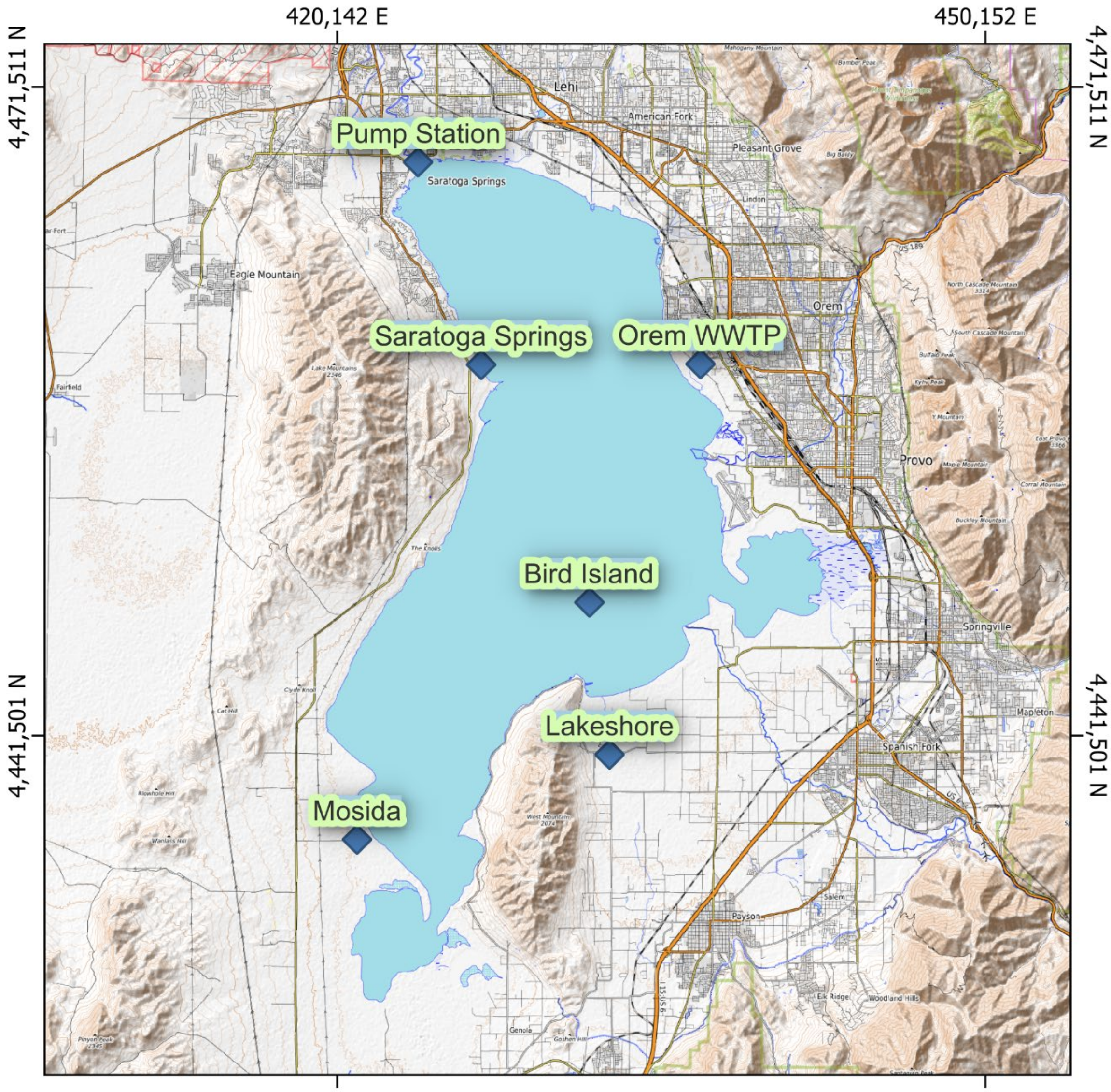

Figure 1.1 The six sampling locations on and around Utah Lake used for this study (data from Bird Island and Saratoga Springs were excluded).

While this study is focused on data from Utah Lake, the findings are applicable to AD nutrient deposition on other freshwater bodies. Understanding how to evaluate and use field data is important.

To determine if the data appear representative or if they are the result of sample contamination, we use several approaches. First, we use statistical distributions to characterize episodic processes for deposition, wind, soil moisture, and precipitation data to see if there are similarities. We evaluate the deposition data in terms of these distributions to evaluate if the data behaves as expected, or if the data deviate from the expected distribution. Next, we evaluate both the deposition data and process data (i.e., wind, precipitation, and soil moisture) to determine if these data are correlated, we use both a visual examination and statistical analysis. Lastly, we look at phosphorous to nitrogen (P:N) ratios. If the samples are contaminated, the ratio of P to N should be different in the contaminated samples.

2 Data and Methods

2.1 AD Data Sampling Locations and Summary Statistics

For this study we analyze the data reported by Barrus, et al. [23] which measured AD from contact, dust, and precipitation sources. These data were measured approximately weekly from 2017 through 2020. Data were taken approximately weekly, though there were some samples with longer intervals. During this period, the Saratoga Springs sampling site was discontinued because of sample contamination and equipment damage [23].

Table 2.1 provides an overview of the dataset. Measurements were made at six different locations, Bird Island, Lakeshore, Mosida, Orem, Pumpstation, and Saratoga Springs (see Figure 1). The samples were analyzed for NO_3, NH_4, Total Nitrogen (TN), soluble reactive phosphorus (SRP), and total phosphorus (TP), though not all samples were analyzed for each analyte. Most combinations of site and analyte had between 125 and 135 samples. Bird Island was only sampled during the final year and only has 15 samples and no data for NO_3 or NH_4. The sampler at Saratoga Springs was vandalized and only has 63 samples. For this study, we focus on the TP data, as phosphorus loads are the most controversial, but the analysis and results are applicable to the other nutrient data collected.

Table 2.1 Samples, with number of samples, mean, and median values for NO_3, NH_4, Total Nitrogen (TN), soluble reactive phosphate (SRP), and total phosphorus (TP) for each sampling location. The data units are mg/m^2.

	NO3			NH4			TIN			SRP			TP		
Location	**N**	**Mn**	**Med**	**N**	**Mn**	**Med**	**N**	**Mn**	**Med**	**N**	**Mn**	**Med**	**N**	**Mn**	**Med**
Bird Island	0	.	.	0	.	.	15	32.0	29.3	15	6.8	3.2	15	17.2	7.3
Lakeshore	125	12.3	8.2	123	44.3	25.2	125	55.9	34.1	126	6.5	2.1	126	10.7	4.7
Mosida	131	10.1	7.9	128	109.4	19.6	131	117.0	27.6	131	12.2	1.8	132	39.1	4.2
Orem	125	12.6	10.2	125	38.4	27.7	123	51.3	37.7	124	5.3	1.8	125	7.6	3.6
Pumpstation	130	12.4	9.3	131	19.1	13.0	131	30.7	21.7	132	3.0	1.2	133	13.2	3.9
Saratoga Springs	63	14.2	9.3	63	208.7	13.1	62	226.5	23.1	63	68.5	3.4	63	200.9	6.0
All	574	12.1	8.8	570	70.0	19.4	587	80.4	28.4	591	13.3	1.8	594	37.3	4.2

Saratoga Springs had enough samples for statistical comparison, and we ran a Tukey-Kramer HSD test to evaluate differences between locations shown in Figure 2.1. We used JMP 16.2 for this analysis [48]. We found that the five largest differences were the parings of the Saratoga Springs site data with other stations. The difference with all five sample locations were statistically significant at the 0.05 level, with all but Bird Island statistically different with a P-value of less than 0.0001. The lower probability that the difference between Saratoga Springs and Bird Island is due to chance is because of the small number of samples for Bird Island, 16. The difference among the remainder of the locations are not statistically significant.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
SaratogaSprings	Orem	193.25	32.54	100.21	286.30	<.0001*
SaratogaSprings	Lakeshore	190.16	32.50	97.23	283.08	<.0001*
SaratogaSprings	Pumpstation	187.63	32.21	95.52	279.74	<.0001*
SaratogaSprings	BirdIsland	183.69	60.51	10.67	356.71	0.0300*
SaratogaSprings	Mosida	161.72	32.25	69.51	253.94	<.0001*
Mosida	Orem	31.53	26.29	-43.63	106.69	0.8371
Mosida	Lakeshore	28.44	26.23	-46.57	103.44	0.8878
Mosida	Pumpstation	25.91	25.88	-48.08	99.89	0.9175
Mosida	BirdIsland	21.97	57.39	-142.12	186.06	0.9989
BirdIsland	Orem	9.56	57.55	-154.99	174.12	1.0000
BirdIsland	Lakeshore	6.47	57.53	-158.02	170.96	1.0000
Pumpstation	Orem	5.62	26.24	-69.40	80.65	0.9999
BirdIsland	Pumpstation	3.94	57.37	-160.09	167.97	1.0000
Lakeshore	Orem	3.10	26.59	-72.93	79.12	1.0000
Pumpstation	Lakeshore	2.53	26.19	-72.34	77.40	1.0000

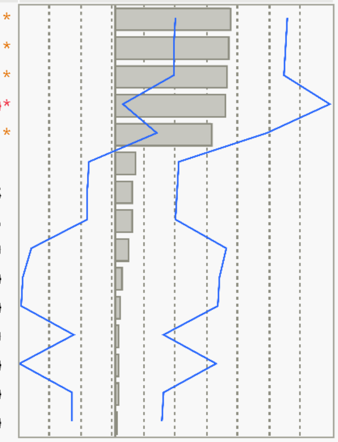

Figure 2.1 Ordered differences report from the Tukey-Kramer test which shows that the TP data from the Saratoga Springs site have the highest difference with all five other sites with the difference statistically significant at the 0.05 level, with most differences significant at the < 0.0001 level.

Based on these clear differences between Saratoga Springs and the remainder of the sites combined with sample contamination and equipment damage, we excluded the Saratoga Springs data from our analyses. We also excluded the data from the Bird Island location because there were only 16 samples taken over a part of the summer sampling season in 2020, though statistical tests showed these data were not significantly different from data at the other sample locations as shown in Figure 2 and [23]. This disparity in the number of samples taken was large enough to make statistically comparisons difficult. Our research goal is to show that AD is an episodic process, strongly influenced by large events. To demonstrate this, we do not need the Bird Island data and they would make comparisons more difficult.

Table 2.2 Samples and descriptive statistics for TP measurements taken at all 6 locations. The bottom line for the Analysis Subset, does not include data from Saratoga Springs or Bird Island. The data units are mg/m^2.

Location	N	Mean	Median	Std Dev	Max	Variance	CV
Bird Island	15	17.16	7.29	28.94	114.46	837.42	168.59
Lakeshore	126	10.70	4.72	20.31	182.15	412.56	189.91
Mosida	132	39.13	4.16	113.33	730.75	12,842.63	289.61
Orem	125	7.60	3.57	13.62	121.17	185.39	179.16
Pumpstation	133	13.22	3.90	75.53	872.37	5,705.15	571.15
Saratoga Springs	63	200.85	6.03	616.50	3396.11	380,076.18	306.94
All Locations	594	37.26	4.15	217.51	3396.11	47,309.89	583.75
Subset of Locs for Analysis	516	17.87	4.12	70.95	872.37	5,033.45	396.98

Table 2.1 provides descriptive statistics for the TP data taken at all six locations including both Saratoga Springs and Bird Island. With the exception of these two excluded stations, the rest of the stations have about 130 samples each, with the range being from 125 to 133 for Orem and Pump Station, respectively. Mean values, excluding Saratoga

Springs, range from 7.60 to 39.13 mg/m^2 for Orem and Mosida, respectively. Median values are significantly lower indicating the data are right skewed, ranging from 3.57 to 4.72 mg/m^2 for Oren and Lakeshore, respectively, excluding Saratoga Springs and Bird Island. The standard deviation, variance and coefficient of variation indicate the Saratoga Springs exhibits the most variation, followed by Mosida and Pump Station. The last two rows of Table 2.1 provide the statistics for all the data (i.e., "All Locations"), and the subset used for analysis which excludes Saratoga Springs and Bird Island (i.e., "Subset of Locs for Analysis"). Excluding Saratoga Springs considerably changes the standard deviation and variative of the data set, from 217.51 to 70.95 and from 47,309.89 to 5,033.45, respectively.

Table 2.3 Sample descriptive statistics for TP measurements taken at all 6 locations. The bottom line for the Analysis Subset, does not include data from Saratoga Springs or Bird Island. The data units are mg/m^2.

Year	N	Mean	Median	Std Dev	Max	Variance	CV
2017	95	24.96	5.83	92.58	872.37	8,570.63	370.91
2018	131	14.03	5.14	26.55	182.15	704.97	189.19
2019	144	27.26	4.76	105.13	730.75	11,051.62	385.67
2020	146	7.44	2.50	23.39	263.12	546.87	314.15

Table 2.2 provides annual descriptive statistics for the subset of locations used for analysis. The number of samples increased each year, with 95 in the 1st year to 146 in the last. Mean values ranged from 7.44 to 27.26 mg/m^2 for 2020 and 2019, respectively with median values ranging from 2.50 to 5.83 mg/m^2 for 2020 and 2017, respectively. The year with the highest mean value, 2019 is different from the year with the highest median value, 2017. This is because the data are not normally distributed, shown below, and extreme values strongly influence the distribution.

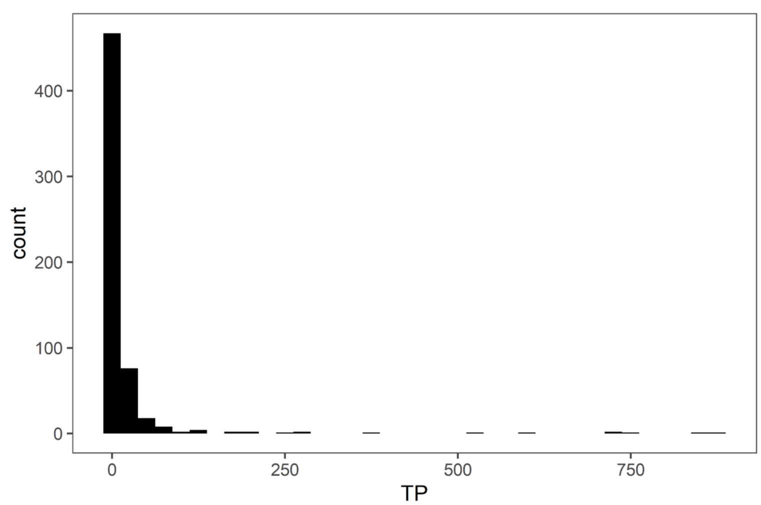

Figure 2.2 Histogram of TP data demonstrating a large right skew, with a long tail.

Figure 2.2 shows the histogram of the data with the majority of the data below 100 mg/m^2 but with values as high as 1,000 mg/m^2. While difficult to count in this figure, there are 11 values between 250 and 1000 mg/m^2. These values in the tail of the distribute are the point of this study as we would like to determine if these values are valid or outliers that should be excluded. This figure only contains the study data and does not include data from Saratoga Springs or Bird Island.

Figure 2.3 is a histogram of log transformation on the P data. This figures shows that while the data are highly skewed nature, the transformation indicates that the data are approximately log normal. If we assume the data are log-normal, then there are five values more than three standard deviations (1.37) from the mean of 1.65.

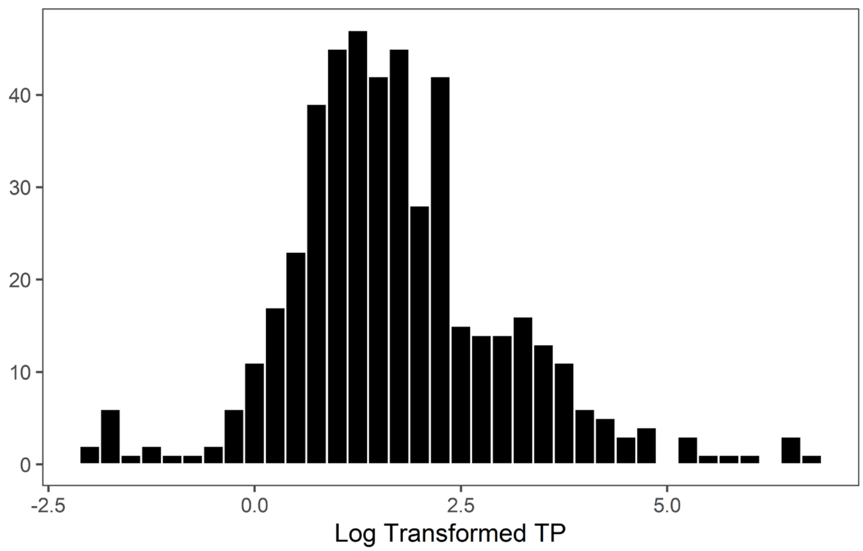

Figure 2.3 Histogram of the log transformed TP data with a mean of 1.65 and a standard deviation of 1.37 if the distribution is assumed to be log-normal.

2.2 Weather Data Acquisition and Description

Since AD is primarily driven by weather patterns, especially wind and precipitation, we investigated correlations between the sample measurements and recorded weather conditions at various stations around Utah Lake . For our analysis, we obtained data from six weather stations around Utah Lake from the Utah State University online climate center [49]. The weather stations were Orem, Lincoln Point, Santaquin, Genola, Goshen, and Tintic (Figure 5)We used the as subset of the available data: maximum wind speed in miles per hour, maximum wind direction, precipitation in inches, and soil wetness as a percentage. The records are available as 10-minute, hourly, and daily data. For the majority of our analysis, we used the 10-minuate data, though for some wind rose plots in the auxiliary material we used the daily average data.

We used the weather data and AD sampling time to calculate the time in hours between samples and during this period the maximum wind speed, the minimum of the maximum wind speed, the maximum of the maximum wind speed, the cumulative precipitation amount, and a sum of the soil wetness percentage. We also computed for each sampling period the number of hours with wind greater than 5, 10, 15, 20, 25, and 30 miles per hour. We computed the parameters for each sample period , so they were generally calculated for a one-week period though some periods were larger.

We created wind roses using the average wind direction and average wind speed from both the 10-minute data and the daily data. We created wind roses using two different wind speed thresholds for visualization as our hypothesis is that large AD events are associated with higher wind speeds. We created and mapped wind roses using all wind speeds represented and with winds greater than 20 miles per hour. Figure 5 shows the wind roses for wind speeds greater than 20miles per hour based on data 10-minute averaged wind data. The wind roses are located on the map near the weather station location (shown as a red pin). We made three additional maps with wind roses. One was of winds 20 greater than miles per hours but created from the daily average wind data. The final two maps included all available average wind data from the daily and 10-minute averaged wind data, respectively. These three wind rose maps are included in the Supplemental Materials.

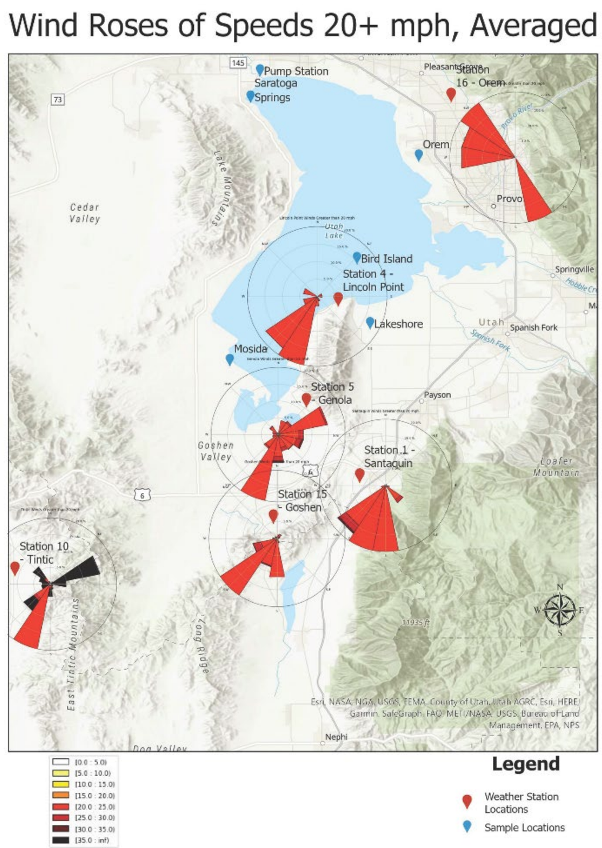

Figure 2.4 Weather station locations and wind roses for wind speeds greater than 20 mph based on 10-minute averaged data

Figure 2.4 shows the AD sample locations (blue pins) and weather station locations (red pins). The wind roses that represent the winds of 20 miles per hour greater computed from the ten-minute averaged data set are located near the weather station locations. Figure 5 shows that higher velocity winds in Utah Valley follow the topography of the valley in a general southwest-northeast in the southern end of the lake following the mountain in that area, and in a northwest-southeast direction in the northeastern end of the lake, again following the mountains in that area. This has implications for AD, as the areas southwest of the lake has significantly more bare soil that areas on the west and north.

We used the 10 minute-averaged data for our analysis as it provides better insight into wind behavior over the day.

2.3 Analysis Methods

2.3.1. Extreme Statistical Distributions

Though there were some particularly high TP values, most of the measurements in our dataset are low, with a median value of 4.12 (Table 2) with a minimum value of 0.13 mg/m^2. The data are very right skewed with a long tail. Figure 4 shows that the data are approximately log-normal, with the best fit to the log-normal distribution having a mean and standard deviation of 1.6 and 1.3 mg/m^2, respectively, with a standard error of fit for the mean and standard deviation of 0.06 and 0.04, respectively.

We used the Log-Pearson Type III distribution, a statistical distribution common to hydrology, to compute return periods for the TP data. A return period is the expected amount of time between events of the given magnitude and is the inverse of expected frequency of an occurrence. The distribution is based on sample period, so in hydrology it is often used to describe the maximum annual flood using a dataset of peak annual flows. In this case, the distribution generates a return period in years. For example, the 10-year flood value has a 10% chance of being exceeded in any given year, while the 50-year and 100-year values have a 2% and 1% chance of exceedance in any year. We assumed our dataset represents roughly weekly sample periods, so the Log Pearson distribution outputs a return period in weeks. This means that the 10-week value has a 10% chance of exceedance in any given week. Return periods should be thought of as inverse expected frequency--or the likelihood of an event—and are not a guaranteed schedule. For example, an event with a return period of 10 weeks has a 1% chance of occurring twice in two weeks. Return periods help illustrate the relative frequency or infrequency of particular events.

To compute return periods for our data we followed the procedure outlined in the text "Hydrology" [50], and the Guidelines for Determining Flood Flow Frequency report from the USGS [51]:

1. Compute the standard deviation, mean, and skew of the log transformed data.
2. Solve Equation 2 for K, where X is the measured TP value for a single observation, log X bar is the average of the log-transformed dataset, and sigma is the standard deviation of the log-transformed dataset.
3. Get the probability of that observation from Appendix 3 of [51] by finding the computed K value in the column for the skew coefficient, which for our data was column G = 0.8.
4. Compute the return period by taking the inverse of the probability.

Equation 2.1 was derived using the Log-Pearson Type III distribution, with details given in [50][51].

$$\log X = \overline{\log X} + K\sigma_{\log X} \qquad \text{Eq 2.1}$$

We also used the Log Pearson procedure to calculate return periods for precipitation and wind data.

2.3.2 Visual Observation

Knowing that high winds occurring after a long period with no precipitation often suspend large amounts of dust from agricultural fields and other areas of bare soil around Utah Lake, we examined the data for periods with these conditions, in which deposition should be more likely occur. We quantified those conditions as low soil moisture and a high number of hours with wind greater than 20 miles per hour. We expected to find instances of TP measurements spiking when samples were collected after a period when these conditions existed.

Since the weather stations from which we collected data were not in the same locations as the AD sampling sites, we had to choose which weather stations to consider as being the most representative of conditions at each sampling site. Due to the complex nature of weather patterns around the lake, statistical and machine learning methods failed to identify significant matches between the sampling sites and weather stations, so we used a more qualitative approach based on visual inspection and knowledge of the topography surrounding the lake. We used the wind rose maps described in Section 2.2 to identify the typical directions of higher speed winds and used that information to identify potential pairings of sampling sites and weather stations. For example, the Lakeshore sampling location is closest in proximity to two weather stations: Lincoln Point and Genola. However, Lakeshore is separated from Lincoln Point and Genola by West Mountain, which rises 2,400 feet above the surface of the lake, so winds measured at those stations are not necessarily as representative of actual conditions at Lakeshore. The Orem weather station, located north of Lakeshore, sits in a clear path in the prevailing wind direction towards Lakeshore, so although it is further away, the wind measured at Orem is likely to be more representative of actual conditions at Lakeshore. are, even though the Orem station is significantly further away. Other pairings were selected using similar reasoning.

2.3.3 Nitrogen to Phosphorus Ratios

In addition to trying to differentiate between valid and potentially contaminated data points with statistical analysis, we examined patterns in the actual nutrient content of the samples. We assume that the composition of the dust being deposited on Utah Lake remains relatively constant over time, so samples with significantly different composition may represent contamination from bird feces, bugs, or other unexpected sources.

A previous study of AD on Utah Lake found that the TP content of soils around Utah Lake is relatively high and constant—around 1 mg of P per 1 g of soil [43], so we assumed that ratios of nitrogen to phosphorus in the samples were likely to be similar. The main sources of contamination, insects, and bird feces, have much higher N:P ratios than local soils, so if a sample has a high N:P ratio relative to the average among all the samples and also had unusually high nutrient levels, we assume it may have been contaminated.

In reality, bird feces and insect bodies do enter the water column as an important component of the nutrient budget [52, 53], so some amount of sample "contamination" from these sources is representative of actual conditions; however, since the physical characteristics of the sampling equipment likely caused increased presence of birds and insects compared to conditions on the open lake, their effect was probably greater than what would be found in other areas. Examining the N:P ratios of the samples provided a rough indicator of samples that were likely contaminated with unusual amounts of bird feces or insect bodies.

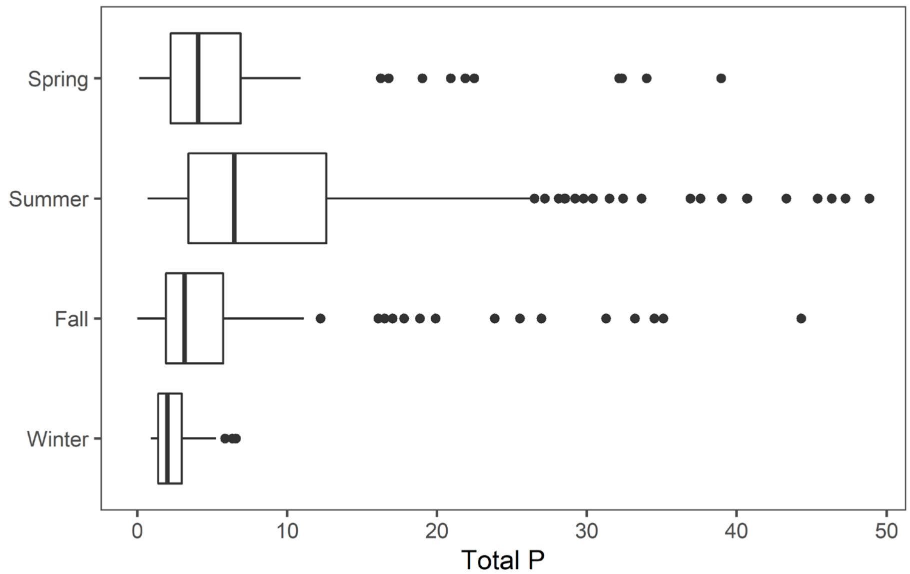

Figure 2.5 Seasonal trend in TP deposition

3 Results

3.1 Seasonal Trends and Return Periods

Since large AD events are more likely during periods when soil is dry and high winds occur, we expected to see higher deposition rates during the summer. This analysis was slightly complicated by the fact that more samples were collected during the summer than the winter, but even with this limitation a clear seasonal trend is present in the data. Figure 6 and Figure 7 show that the samples with the largest volumes of TP were collected during the summer months. This is likely due to the long dry spells Utah Valley experiences in the summer, which exacerbate suspension of dust by strong winds. Several samples with concentrations well above 50 mg/m^2 of TP were excluded from the image in order to make the seasonal trend visible.

Figures 2.5 and 3.1 show that the majority of the samples gave TP results at the lower end of the measurement range, with a handful of unusually high measurements mostly occurring during midsummer. Analysis of the return periods for specific concentrations of TP provides some insight into the frequency with which AD events of various sizes occur.

Table 3.1 shows a summary of the six observed concentrations with a return period of greater than 100 weeks, their respective total P measurements, and the number of standard deviations they are from the log-transformed mean. The return periods were calculated using the Log Pearson procedure, described in Section 2.1.1. Too many observations with high return periods could be cause for concern, however we observed only 6 high return period observations out of 516 total observations, or 1.1%.

The return period of the highest observed measurement, 872.37 mg/m^2 on June 29th, 2017, has a return period of 400 weeks, which indicates that a sample concentration that large would typically only be observed every 8 years. This is significant, but not unreasonable; however, later analysis with N:P ratios (detailed below) showed that this sample was likely affected by contamination and is not a valid data point.

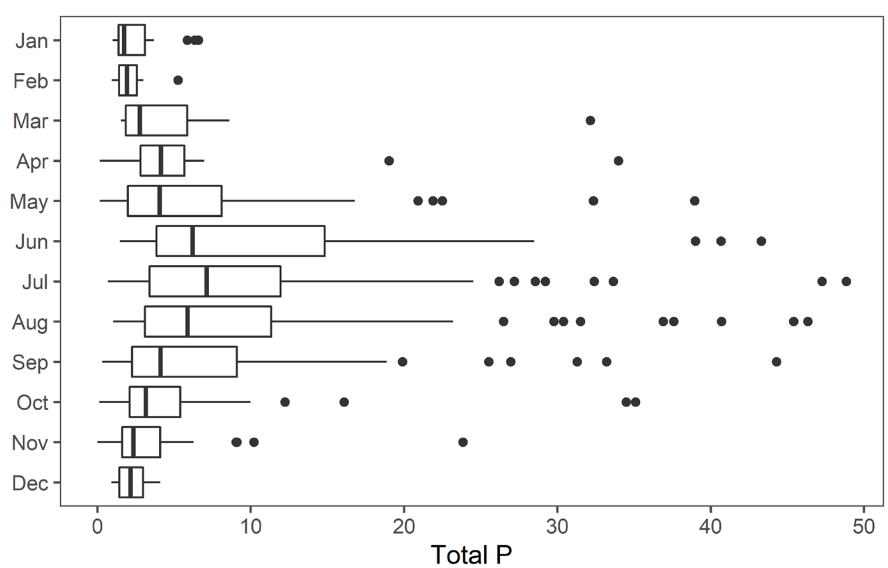

Figure 3.1 Monthly trend in TP deposition

Note that five of the six highest measurements in the dataset occurred in July and early August of 2019 at the Mosida site. This is not surprising for a number of reasons. Out of all of the sampling sites, Mosida is the closest to large dust sources from the desert area west of Utah Lake. It is also the most isolated site, away from built-up areas that decrease wind speeds and intercept dust. In addition, 2019 was a significant drought year, and it is likely that the dry conditions increased the amount of suspended dust and sediment.

Table 3.1: High return period observations

Date	Location	TP (mg/ m2)	Return Period (Weeks)	St Dev's from Mean
6/29/2017	Pump Station	872.37	400.0	3.75
7/12/2019	Mosida	730.75	312.5	3.62
8/2/2019	Mosida	729.80	312.0	3.61
8/9/2019	Mosida	608.38	256.4	3.48
8/16/2019	Mosida	366.20	143.2	3.11
7/5/2019	Mosida	282.44	104.2	2.92

Figure 3.2 is a time series scatterplot of return periods for total P at all sampling locations. It shows that of the 516 observations in the log-transformed data, only 6 have a return period of greater than 100 weeks. We also calculated the Log-Pearson Type III distribution for the weather data but found there to be only one rain event and four wind events greater than 20 miles an hour with a return period of greater than 100 weeks. None of these high return period weather events correspond to the high return period deposition events, so we did not factor them into our analysis. Figure 3.2 also reinforces the highly seasonal trend present in AD on Utah Lake, with the most impactful events occurring during midsummer. The gaps in the data over the winters are due to the lack of sampling during those times.

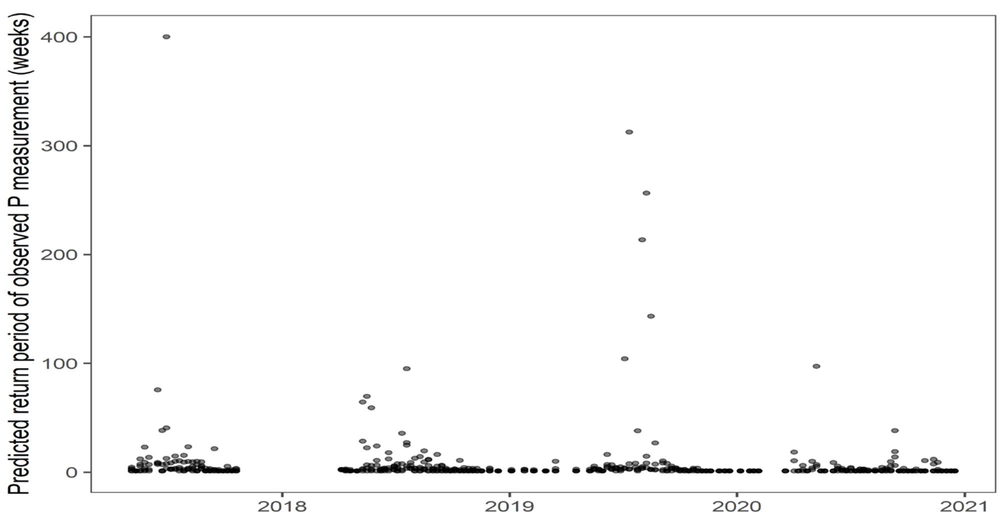

Figure 3.2 Sample return periods

3.2 Correlations Results

As the analysis of seasonal trends and return periods shows a clear connection between AD and prevailing weather conditions, we investigated this condition with visual analysis of AD measurements and weather data. Figure 8 shows total P measured at the Lakeshore site and wind and soil moisture recorded at the Orem weather station over the duration of the study period. The wind observations are the number of hours prior to sample collection with wind speed greater than 20 miles per hour (mph). The surface wetness is expressed as a percentage. For this study we summed the percent wetness values over the sampling period.

We chose Orem as the matched weather station for Lakeshore based on physical proximity, inspection of the topography, and the wind rose maps, as explained in Section 2.2. The vast majority of the high winds in these stations near Lakeshore blow in a southern direction. This is because of the mountain between Lakeshore and this part of Utah Valley. The winds follow the terrain south, directing them away from the Lakeshore station slightly north (Figure 5). This makes the Orem station the best weather station for wind and soil moisture data at the Lakeshore station.

We expected to see more high-speed winds and lower soil moisture during the period before sample collections which showed larger volumes of deposited phosphorus. This correlation was present with varying intensity throughout the study period. Figure 3.2 illustrates this pattern the most clearly, showing the irregular, episodic relationship between weather and phosphorus deposition on Utah Lake. The first large spike in winds greater than 20 mph is at the exact time as the largest spike in phosphorus deposition and occurs at a relatively low point in soil moisture. The two other largest peaks in wind, which we would normally expect to cause increased deposition, show no increase in total P—but note that they occurred at the same time as the largest peaks in soil moisture. This provides evidence for the assumption that high wind alone is not sufficient to cause a large deposition event; but rather the combination of dry soils and high wind drives the largest events.

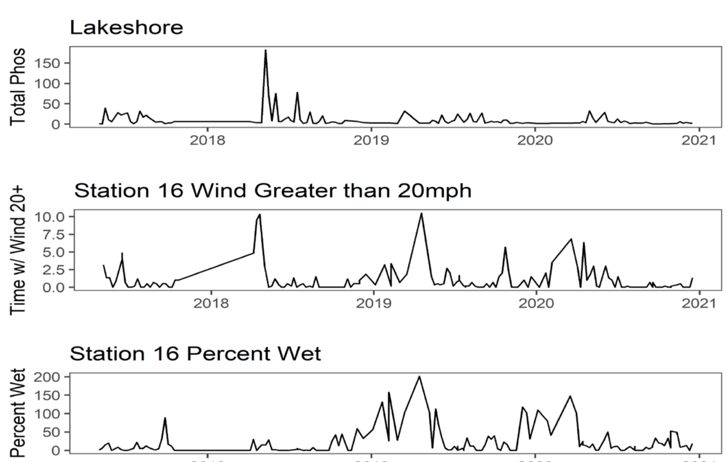

Figure 3.3 Lakeshore sampling location time series plotted on top of high wind and soil moisture time series from the Orem weather station.

3.3 Nitrogen to Phosphorus Ratio Results

Another correlation we investigated was that between total phosphorus and the total inorganic nitrogen to total phosphorus (TIN/TP) ratios, as described in Section 2.5. Looking at the time series for these two parameters helped us identify which high phosphorus measurements are legitimate, and which may have been caused by contamination.

Although Figure 9 shows some large changes in the N:P ratio for particular samples, none of these samples were abnormally high observations, and so we do not consider them to be at risk of possible contamination.

The same analysis with data from Mosida (Figure 3.4) yielded a similar result, even though Mosida had several high return period observations, unlike Orem.

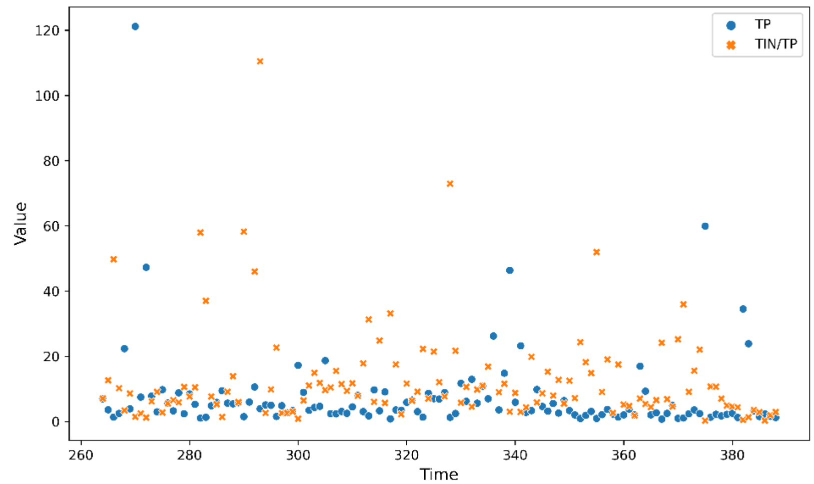

Figure 3.4 shows a time series of total P and a calculated TIN/TP value, both from the Orem sampling station. There were no large observations at the Orem site (relative to other site) throughout the duration of the study period, so we considered these measurements to be representative of "background" deposition. There is some noise, but when taking the scale of the y-axis into account, none of the high-looking values are actually unusual.

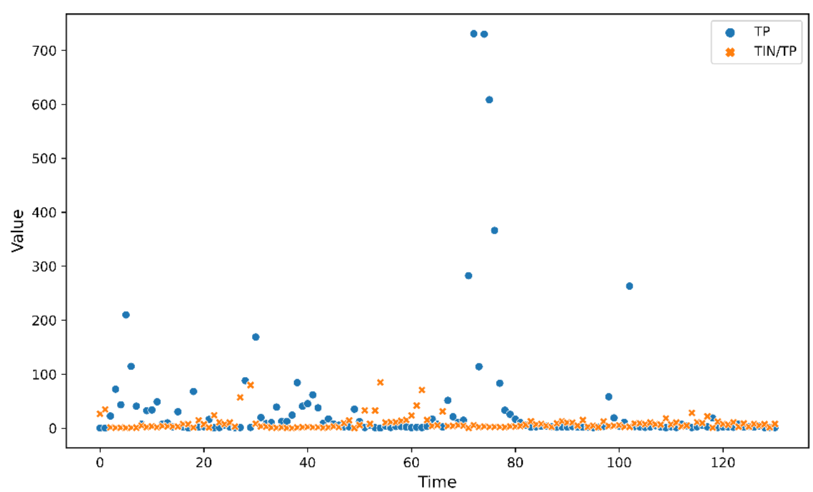

Figure 3.5 TP and N:P time series plots from the Mosida sampling location

Figure 3.4 shows the handful of unusually high total P measurements over the study period, with no significant change in the TIN/TP ratio associated with those measurements. The stable N:P ratio at the same time of the high observations suggests that contamination was not the cause of the unusually high values, and they are legitimate observations of large AD events.

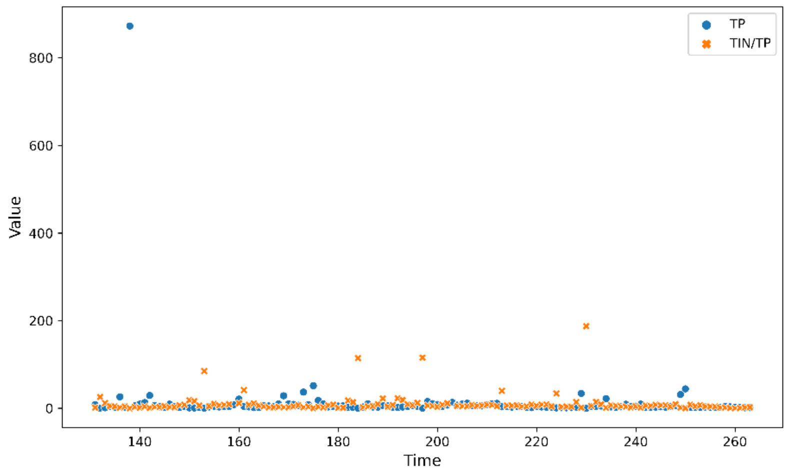

Figure 3.6 TP and P:N time series plots from the Pumpstation sampling location

The time series graph for the Pumpstation (Figure 3.5 shows one observation that is clearly much larger than any other observation from). At this scale, it is difficult to see in the P:N ratio, but a plot of the ratio by itself reveals a large change in the ratio for the high sample.

P:N ratios were calculated for the other two stations but were not included because they showed the same trend as the N:P ratios. Though a ratio reading of approximately 65 is not high in absolute value terms, it is more than 6 times higher than any other ratio in the data set for Pumpstation. This appears to be a clear indication of contamination, meaning that the abnormally high observation at Pumpstation is likely a bad data point which should be excluded.

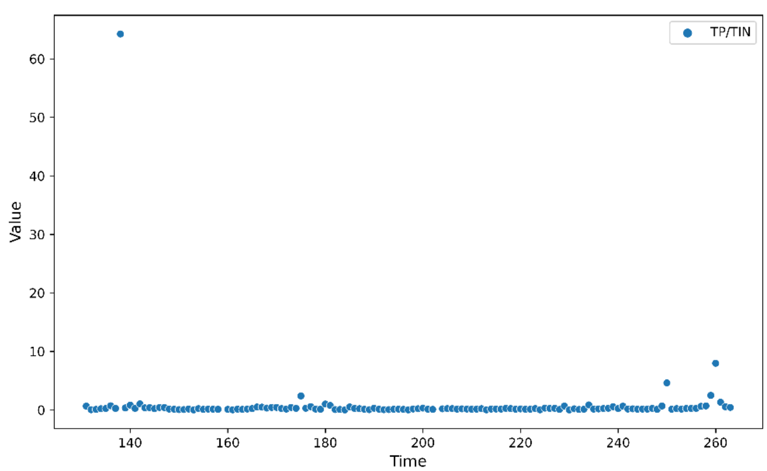

Figure 3.7 P:N time series plot from the Pumpstation sampling location

3.4 Cumulative volume analysis

In the field of hydrology, cumulative precipitation plots ordered by event size are commonly used to show the outsize volume contributed by a few very large events during a year. Often, the distribution is such that roughly 80% of the annual precipitation volume falls during 20% of the storms. AD is a similar process in that most of the annual load occurs during a handful of very large events. This is clearly illustrated with a cumulative deposition plot ordered by event size (Figure 3.8). This graph was created by ordering the sample observations from largest P concentration to smallest, and then calculating the cumulative sum for each observation and plotting it against the sample number (expressed as a percentage of the total number of samples for better visualization). Cumulative precipitation is also shown to emphasize the similarity between these two processes.

They both seem to follow the 80/20 rule fairly closely. The precipitation data in particular show the high importance of relative extreme values with its particularly steep slope until the large number observations with no precipitation, shown by the flat part of the line at the top. This rule is verified by finding the 80th percentile of deposition. This came out to be 6,679 mg. That threshold is crossed by the 99th observation when ordered by TP. 99 out of 516 observations is 19.2%, meaning it took only 19.2% of observations to get 80% of the total deposition.

Just as removing the 20% of storms with the highest precipitation volume would dramatically misrepresent the water budget for an area, removing the highest AD observations would significantly decrease the accuracy of the Utah Lake nutrient budget.

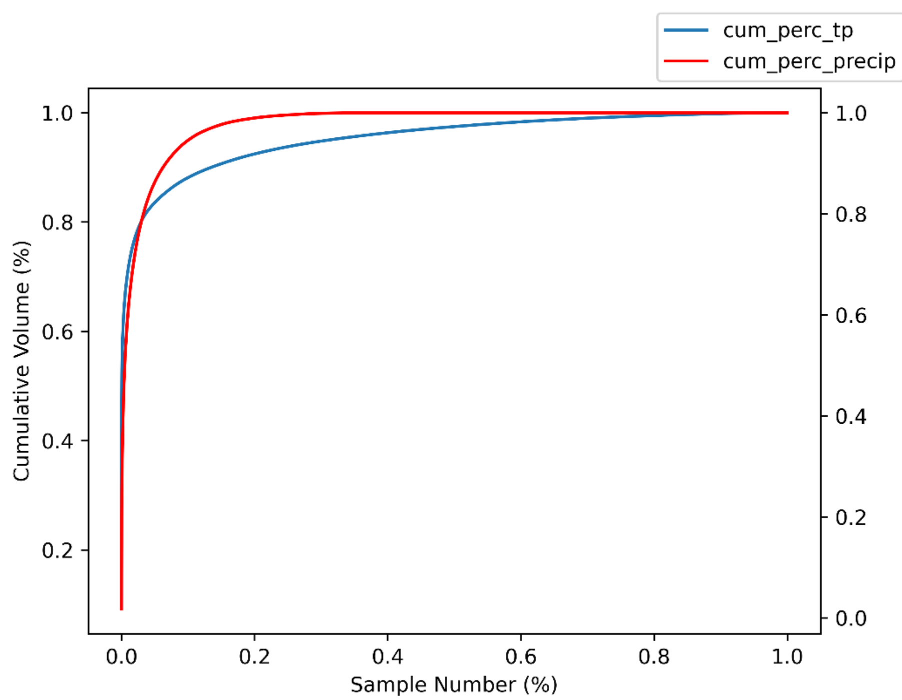

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Figure 3.8 Plot of cumulative TP deposition and precipitation. Red line is precipitation and blue line is TP.

4 Discussion

Multiple studies of AD on Utah Lake have resulted in various estimates of TP deposition on Utah Lake. Of these studies, Barrus, et al[23], used a sampling method that best approximated the total load to Utah Lake from the three deposition pathways (settlement, contact, and washout), and also has the most site-specific data, with sampling locations close to the lake. We used this data in conjunction with comprehensive local weather data to better understand and estimate AD-related annual loads of total P to the lake.

Visual inspection, though not a quantitative measure, provides the best visual representation of the weather conditions that cause large deposition evens on Utah Lake. Long periods of dry weather facilitate increased suspension of dust from areas of bare soil, which can enter the lake through settlement or washout during the next precipitation event. Because of this, periods of no precipitation, resulting in low soil moisture, combined with high winds create a largest deposition event. Large deposition events also occur when a rainstorm follows a longer dry spell and washes out suspended dust and aerosols. While difficult to quantify precisely, these patterns are apparent in the data and are some of the most important driving factors of AD on Utah Lake.

Analysis of nitrogen to phosphorus ratios in the samples, which are an indicator of possible sample contamination, showed that the largest measurement in the dataset had a significant change in the ratio. This suggests that this single very large measurement, from the Pumpstation sampling site, is likely a bad datapoint and should not be included in estimates of the total AD load to Utah Lake. The next 5 highest observations, however, showed no change in the P:N ratio relative to the average ratio for the rest of the samples, indicating that these high measurements are valid datapoints that represent infrequent but very large AD events on Utah Lake.

The Log-Pearson Type III extreme value distribution, while not a common analysis tool outside of the field of hydrology, is useful for categorizing the probability of a particular event occurring. Discounting the contaminated Pumpstation sample, the observation with the highest return period has a return period of 312.5 weeks. With a data set spanning approximately four years, or a little over 200 weeks, having three observations with return periods greater than that span is well within the bounds of reason. We expect there to be a few high return periods in most AD data sets, because all or most of the annual AD volume can potentially occur in just one or two events. The other two high Mosida observations both have return periods equal to or less than the number of weeks in the study. This shows that the high observations are the result of large, episodic deposition events.

Cumulative volume analysis, while also not common outside of hydrology, helpfully illustrates how AD follows the "80/20" rule, where 80% of the total load is observed in just 20% of the measurements. Just as how the top 20% of rainfall events contribute most of the annual precipitation volume, the top 20% of AD events contribute most of the total load and must be considered as part of an accurate nutrient budget.

There is a significant overlap between the methods in terms of what they identified. Each only identified a handful of observations with the potential need for exclusion. These analysis methods combine to provide a comprehensive assessment of which observations are potentially contaminated, and of the episodic nature of atmospheric deposition on Utah Lake.

5 Conclusions

This research helps answered two questions:

1. How much, if any, of the data from prior studies should be excluded from estimating the AD-related nutrient load to Utah Lake, and
2. Does AD have an episodic trend and correlation with local weather conditions.

To address these questions, we performed an analysis using four different methods: visual observation, N:P ratios, the Log-Pearson Type III extreme value distribution, and cumulative volume plots. We used wind roses from local weather stations to find the best weather station-sampling location pair for each sampling location. We used that pairing to look for large deposition events at the same time as high wind events and low soil moisture. We also used N:P and P:N ratios to identify potential contamination from insect bodies or bird feces in high TP observations. Finally, we calculated return periods for each observation using the Log-Pearson distribution.

Our search for the deposition-wind pattern in the different locations yielded mixed results. The pattern of the clearest example, shown in Figure 8, was also found to various degrees in a handful of other location-weather station pairings but was not found in a majority of the pairings. Large events can and do occur when this condition of high winds at times of low soil moisture is not present but are most likely to occur when those conditions are present because they represent the ideal conditions for large deposition events. This pattern is an important part of episodic AD on Utah Lake.

We used N:P and P:N ratios to specifically look for contamination in our samples. We looked for a significant change in ratio at the time of a large observation. We only found this significant change in ratio with the large Pumpstation observation from June of 2017. We believe that that observation represents organic contamination and should be excluded from future analysis. The 5 high Mosida values all occurred at times when the ratios stayed approximately constant, so we believe these values should remain in the data set and be recognized as legitimate AD observations.

We used the Log-Pearson to get return periods for each observation in our data set. When we did that, we only found 6 of them had a return period of great than 100 weeks (Table 4). One of them, the Pumpstation observation from 2017, had a return period of 400 weeks. We have since labeled this observation as contaminated, so excluding it, the two highest observations have return periods of approximately 312 weeks. These, as well as one observation with a return period of 256 weeks, represent the only 3 observations with a return period significantly higher than the number of weeks in the study, approximately 200. The other two high observations are both within time frame of the study. Because it is expected to have a handful of low-probability events in such a long time period, we believe these observations are within a reasonable realm of possibility and see no reason they should be excluded.

Our results confirm that the data from Barrus, et. al[23]. accurately represents AD-related nutrient loads to Utah Lake. Observations with a reasonable TIN/TP ratio and a high Log-Pearson Type III return period are infrequent but legitimate observations. There was only one observation, from the Pumpstation sampling site, which shows evidence of being contaminated and not representative of actual conditions. This does not include any observations from Saratoga Springs, which we excluded because it was significantly different from all other sampling locations, or from Bird Island, which we did not analyze due to its small number of samples. Bird Island is likely no different from the rest of the locations, but there were not enough samples to analyze alongside the other locations. Outside of the Pumpstation sample, our analysis showed that the rest of the data are legitimate and should be recognized as representative of the total phosphorus atmospheric deposition load on Utah Lake. Our analysis also shows the episodic nature of the atmospheric deposition and how local weather events greatly affect large deposition events on Utah Lake.

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