Proposal to Measure Atmospheric Deposition in Utah Lake

Theron Miller, PhD

Wasatch Front Water Quality Council

Prepared for the Utah Lake Science Panel

April, 2019

Introduction

The National Atmospheric Deposition Program (NADP; http://nadp.slh.wisc.edu/NADP/) was organized in 1977 and sites in the NADP precipitation chemistry network began operations in 1978. The goal was to provide data on the amounts, trends, and geographic distributions of acids, nutrients, and base cations in precipitation. Notably, although measuring nutrients was listed as a primary goal, only nitrate was originally measured and ammonia measurement didn't begin until 2009. While efforts to develop dry deposition sampling protocols are apparently underway and similarly, efforts to add phosphorus to the list of analytes has been mentioned; there are currently no dry deposition or phosphorus data listed on the NADP website. The Manual states "The networks associated with the NADP consider wet-deposition (AIRMoN, MDN, and NTN), atmospheric mercury (AMNet), and atmospheric ammonia (AMoN). Selection of monitoring sites within the NADP is based on the site's potential to: provide insight into changing atmospheric chemistry, help assess the contributions to sensitive ecosystems, and help validate atmospheric models. Of particular interest are major ***physiographic, agricultural, aquatic***, and forested ***areas within states, regions, and ecoregions***." (emphasis added). Table 1 is excerpted from the NADP site selection and Installation Manual.

Table 1. NADP Site Classifications.

Site Classification	Population within 15km of the site (people/km^2)
Isolated (I)	< 10
Rural (R)	10 – 99
Suburban (S)	100 – 399
Urban (U)	≥ 400
Research/Provisional (P)	na

After collecting dry deposition samples in our program for 2.5 years, I clearly understand why standard protocols have NOT been established for dry deposition. There are myriad variables associated with dry deposition sampling and existing reports that include dry deposition only describe specific methods to meet specific project goals. These include, but are not limited to: near and far field agricultural activities, (Winter et al. 2002, Anderson and Downing, 2006; i.e. plowing and tilling can be a source of dust and between plantings, bare soil can be a significant source of dust during wind events). The dust flux in an arid urbanizing area may be as much as twice that before disturbance but decreases when construction stops (Reheis and Kihl 1995). In addition to just the dust, some studies have determined that dry deposition may contain more P and N than wet deposition samples (Ahn and James 2001; Anderson and Downing 2006; Winter et al. 2002). Urban environment sources are important sources of particularly nitrogen from auto exhaust as well as industrial sources (Reheis and Kihl 1995). Conversely, in higher precipitation areas, wet deposition is the most dominant form of deposition and generally reflects long-range transport, while dry deposition is more linked to local pollution levels (Balistrini et al. 1995). The degree to which all of these observations could apply to Utah Lake is important in that Utah Lake resides in an arid environment as well as adjacent to a highly urbanized and moderately industrialized area, as well as exposed to dust that can be transported from distant sources.

Several reports indicate that dust can travel great distances. Much of this evidence has been collected comparing wet and dry deposition in the Iberian Peninsula. Dry deposition can be ignored compared with wet deposition in arid or semi-arid regions. Loye-Pilot and Martin (1996) suggest that in rainy areas dry deposition can be ignored, but dry deposition can be the dominant fraction in arid and semiarid regions where intense dust loadings take place and it is necessary to separate wet and dry deposition (Loye-Pilot and Martin 1996). Dry deposition can dominate the atmospheric delivery of particulate matter, including total phosphorous, Ca^{2+}, Mg^{2+}, and K^{+} in the Sahara Desert (Morale-Baquero, et al. 2013). It is noteworthy that the sampling area, in the Sierra Nevada Mountains of southern Spain, is approximately 160 km from the north shore of Africa (the source being identified as the Sahara Desert). Despite this distance, the mean of 108 samples over two years was 23.6 mg m^{-2} day^{-1} of total particulate matter in dry deposition samplers (range = 0.3–105.8 mg m^{-2} day^{-1}) and 6.8 mg m^{-2} day^{-1} in wet deposition samples (range = 0.0–95.8 mg m^{-2} day^{-1}). Of this total particulate matter, approximately 50 ug or 0.16% was P (Morale-Baquero, et al. 2013).

One of the most extreme examples of dry deposition lies in the evidence of transcontinental transport (Yu et al. 2015). They based their estimate on 3-D distributions of aerosols from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) from 2007 to 2013. This was an improvement on the previous standard for satellite estimates of dust deposition using the Moderate Resolution Imaging Spectroradiometer (MODIS) that provides only a two-dimensional view of the transport [Remer et al., 2005]. In short, from the 7-year study the annual average deposition of North African dust in the Amazon (i.e. excluding local sources from fires, etc.), was estimated to be 28.9 kg ha^{-1} yr^{-1}. Furthermore, based on analysis of the dust in the Sahara, the deposition of P in the Amazon Basin was estimated at 780 ppm (Bristow et al., 2010).

In the US, one of the most noted examples of mobilized sediment/dust from Owens Lake (Figure 3). The average silt and clay flux (rate of deposition) in southern Nevada and southeastern California ranges from 4.3 to 15.7 g m^{-2} yr^{-1}, but in southwestern California the average silt and clay flux is as high as 30 g m^{-2} yr^{-1} (Reheis et al. 1995). Documentation of the Owens Lake diversion debacle is a clear example. The dried lake bed of Owens Lake in Inyo County, California, has been identified as the likely largest single source of particulate matter pollution in the United States (U.S. Environmental Protection Agency (EPA), Air Data, 2003, available at http:// www.epa.gov/air/data). Gillette et al. (2004), from a combined modeling and measurement process, estimated that 1×10^6 to 3.8×10^6 t of dust $year^{-1}$ are emitted from lake bed of Owens Lake. Dust emissions from single storms have been estimated at 80,000 t (Figure 3). How far does this dust travel? Reheis (1997) estimated deposition rates at a sampling site approximately 40 km downwind from Owens Lake to be about 20-25 mg m^{-2} d^{-1} during 1992. After a fire in the vicinity occurred during the 1992-93 winter the total dust flux increased to 30-40 mg m^{-2} d^{-1}. Notably, however, by May 1993 wind had completely stripped the burn surfaces of fine soil particles and charcoal and deposition returned to the 1992 values (Gillette et al. 2004).

While no estimates of P concentrations in Owens Lake dust could be found, it may be reasonable to assume that Owens Lake has been part of a terminal lake system for many thousands of years or beyond, and hence P concentrations in dust may be similar among Great Basin terminal lakes. Sediment samples in and around Utah Lake have been reported by Abu-Hmeidan et al. (2018). The mean of 93 samples = 690 mg kg^{-1}. Abu-Hmeidan et al. (2018) believed that these samples were remnants of ancient Lake Bonneville sediments, which most recently formed during the last part of the last ice age at about 25,000 years ago. However, Lake Bonneville was large, covering nearly half of Utah (Figure 1) and included, in addition to Great Salt Lake and Utah Lake, the currently dry remnant of Lake Bonneville, Sevier Lake, located in west-central Utah, about 160 km SW of Utah Lake (Figure 2). Figure 2 also shows the location of the current NADP sampling sites in Utah (NE Utah, Eastern Uinta Mountains, Green River, Canyonlands NP and Bryce NP). All of the sampling sites are in the northern or eastern parts of Utah, far away and over at least one mountain range from ancient Lake Bonneville, hence there is minimal influence from Lake Bonneville sediments at these sites. Alternatively, with minimal topographic impedence, Utah Lake is likely continuing to be supplied with phosphorus-rich dust from the dry lake bed of Sevier Lake. For example, as reported in the Deseret News on April 16, of 2018:

"SALT LAKE CITY — High winds carried dust from a dry lake in Millard County to the Wasatch Front, where multiple counties had pollution warnings in effect due to the dust storms. The National Weather Service in Salt Lake City said much of the dust along the Wasatch Front was the result of winds whipping up dust from the dry Sevier Lake."

The location of Utah Lake, in the heart of the Lake Bonneville footprint and located immediately downwind (NE) of Sevier Lake, should be of critical interest. Yet, today, there are apparently no

NADP sites within 150 miles of Sevier Lake or Utah Lake. The five NADP sites in Utah are located in the north east (near Logan), in the eastern Uinta Mountains, near Green River, in Canyonlands National Park, and Bryce Canyon National Park, all in eastern Utah. Even if P were analyzed in these samples, data would represent only broad regional to multi-state-scale deposition, with little regard to sources and particularly the dry lake bed of Lake Bonneville. This is profoundly different from the objective of quantifying atmospheric loading from both local and regional sources that appear to contribute significant quantities of dust and nutrients to Utah Lake.

Furthermore, dust mobilized from a dry lake bed such as Owens Lake or Sevier Lake can amount to many thousands of tons of dust per year and with this being sedimentary dust, it likely contains 600 to 800 mg P kg^{-1}. For comparison Sevier Lake is located approximately 150 km SW from Utah Lake (equidistant as that between the Sahara Desert and Southern Spain for comparison). Moreover, the dry lake bed of Sevier Lake is large, about 1.6 X larger than that of Owens Lake, CA, (453 vs 280 km^{-2}), and much larger than Utah Lake itself (383 km^{-2}). Hence, the likelihood that Sevier Lake sediments reach Utah Valley is strong. The two remaining questions are: What is the dust load that reaches Utah Lake and what are the loads of P and N?

In addition, as suggested by Balistrini et al. (1995), Local sources may also be important. This would be particularly true in the enclosed Utah and Salt Lake Valleys where temperature inversions, leading to smog alerts, are common during winter (Figure 4) and auto emissions are known to be a key contributor of ammonia to the atmosphere (e.g. Durbin et al. 2001).

One of the unique conditions of Utah Lake is its location in Utah Valley. As a high elevation valley (elevation circa 4490 ft), surrounded on most of four sides by hills or mountains 6000 ft to 12000 ft elevation, Utah County experiences severe temperature inversions very frequently for several months each winter (e.g. Figure 4). These inversions occur up and down the Wasatch Front and consistently trap particulate and chemical pollutants. While vertical mixing is impeded by temperature stratification, horizontal movement easily distributes such inversion smog uniformly across the valley and Utah Lake.

Dr. Wood Miller, Professor of Engineering, BYU has collected bulk atmospheric deposition samples from 9 locations surrounding Utah Lake over the last 2.5 years. These particular samplers included a funnel with the mouth approximately 1.5 ft in diameter leading to a storage cylinder. Samples were retrieved after each rainfall. Unlike the bulk deposition samplers designed and used by USGS, it is possible that dust that settles on the slope of the funnel could get resuspended with successive winds and lost to the sample; hence providing a conservative estimate of deposition. Yet, overall mean concentrations among all sites and 299 samples were 0.798 mg/L for TP and 3.289 mg/L for TN (unpublished data). With an estimated 16 inches average annual rainfall, this amounts to conservative estimate of approximately 110 tons of P added to the lake surface annually. Notably, the three sites with the lowest values for P were 400 ft or more above the lake surface elevation, while the others were nearer to the lake, a possible reflection of the effect of inversions as well as the proximity to an urban environment and active construction and agriculture.

The proportion of contribution from intra-basin transfers from the sediments of ancient Lake Bonneville or from local airshed sources, (e.g. agriculture, construction, etc. including rural and suburban and urban) remains to be more carefully evaluated. But with Utah County often being awarded the distinction of being the fastest growing urban population in the US, these urban disturbances, encroaching further and further upon the shorelines of Utah Lake, this activity is highly unlikely to chance any time in the near future and it is our responsibility to develop an accurate accounting of these potential sources of nutrients to the Lake.

Aquatic ecosystems, such as Utah Lake, near major physiographic sources (e.g. Sevier Lake), agricultural areas or adjacent urbanized and urbanizing areas, and subject to frequent inversions should be of key interest.

Another issue concerning atmospheric deposition involves the decision as to whether the contribution of insects should be included. There are situations where insect and other terrestrial debris can significantly influence a lake's nutrient budget. Cole et al. (1990) found that particles (consisting largely of terrestrial insects, insect parts and plant fragments contributed 50 to 70 times more input of P than either streamflow or rainfall in a small New Hampshire lake. On the other hand, Dreyer et al. (2015) used emergence traps to estimate biomass and nutrients leaving a lake and aerial in-fall traps to measure the deposition of insects over the land. Emergence rates ranged from 0.15–3.7 g m^{-2} yr^{-1}, or a whole-lake emergence of 3.1–76 Mg dry mass yr^{-1}. They developed a local-maximum decay function model to predict proportional midge deposition with distance from the lake. The dispersal model predicted midge abundance with $R^2 = 0.89$. Notably the peak midge deposition occurred 20–25 m inland and 70% of midges deposited within 100 m of shore. During a "high-midge year" (2008), they estimated midge deposition within the first 50 m of shoreline to be 100 kg ha^{-1} yr^{-1}, corresponding to inputs of 10 kg N ha^{-1} yr^{-1} and 1 kg P ha^{-1} yr^{-1}, or about three to five times above background terrestrial N deposition rates.

It could be debated whether the mass movement and deposition of insects in less than 100 m from shore constitutes removal of nutrients from the lake's ecosystem, particularly in the case of Utah Lake, where the first upland 100 m is generally a mere 10-20 vertical cm from the shoreline elevation and Utah lake swells and declines an average of 70 cm each year-inundating at least the first 100 m of most of the Utah Lake shoreline.

Clearly, there are instances where the contribution of insects, whether of terrestrial or aquatic origin, are important to the nutrient budget of lakes. In the case of Utah Lake, there are terrestrial insects (e.g. Hymenoptera) that inhabit an adjacent farm on the west side of the lake that drift over and settle on the lake surface. In addition, though more concentrated in the littoral zone, the entire bottom of Utah lake is colonized by an estimated 6000 tons of midges (family Chironomidae; Richards, unpublished data). At 1% P by weight, an estimated 60 tons of P are recycled from the sediment detritus by the nearly continuous emergence from multivoltine, detritus-feeding midge species during the growing season. Yet, this may be followed by the potential return of 70% or more of the nutrients (estimated from Dreyer et al. 2015), because of the shallow upland gradient and the real likelihood that next year's spring runoff will inundate the same 100 m with lake water. This could potentially mobilize a significant portion of the nutrients from the previously deposited insects – or buried in place, facilitated by the senescing and litter-fall of the vast stands of phragmites. We just don't know.

Either way, it may be important to develop an appropriate dispersion equation to estimate the distance that returning adults 'rain' upon the lake surface and to what degree nutrients from emergent production returns to the lake. This will depend on local weather conditions during emergence, shoreline vegetation type and condition, and predation from avian and other species, among other factors. Although to a much smaller scale, the degree that nutrients are recycled from insect emergence can be compared to recently documented sediment nutrient recycling by Hogsett, et al. (2018), where they estimated the release of 1500 tons of SRP from Utah Lake sediments. Clearly, this release is only half of the equation. There must be a similar but reversal of the process that characterizes a return of P to the sediments in rapid order. Otherwise, the lake would have much greater water column concentrations and would be in the process of purging available nutrients within years or a few decades. Moreover, estimates of nutrient retention in Utah Lake have varied from 70% (Hogsett 2018) to 90% (Merritt, unpublished data) based on mass balance data and models.

This review clearly reveals the importance of both wet and dry deposition as well as establishing a reasonable estimate of recycling nutrients from insect emergence as well as direct nutrient recycling from sediments.

SOURCE: UTAH GEOLOGICAL SURVEY

Figure 1. Location of ancient Lake Bonneville, current Great Salt Lake and Utah Lake.

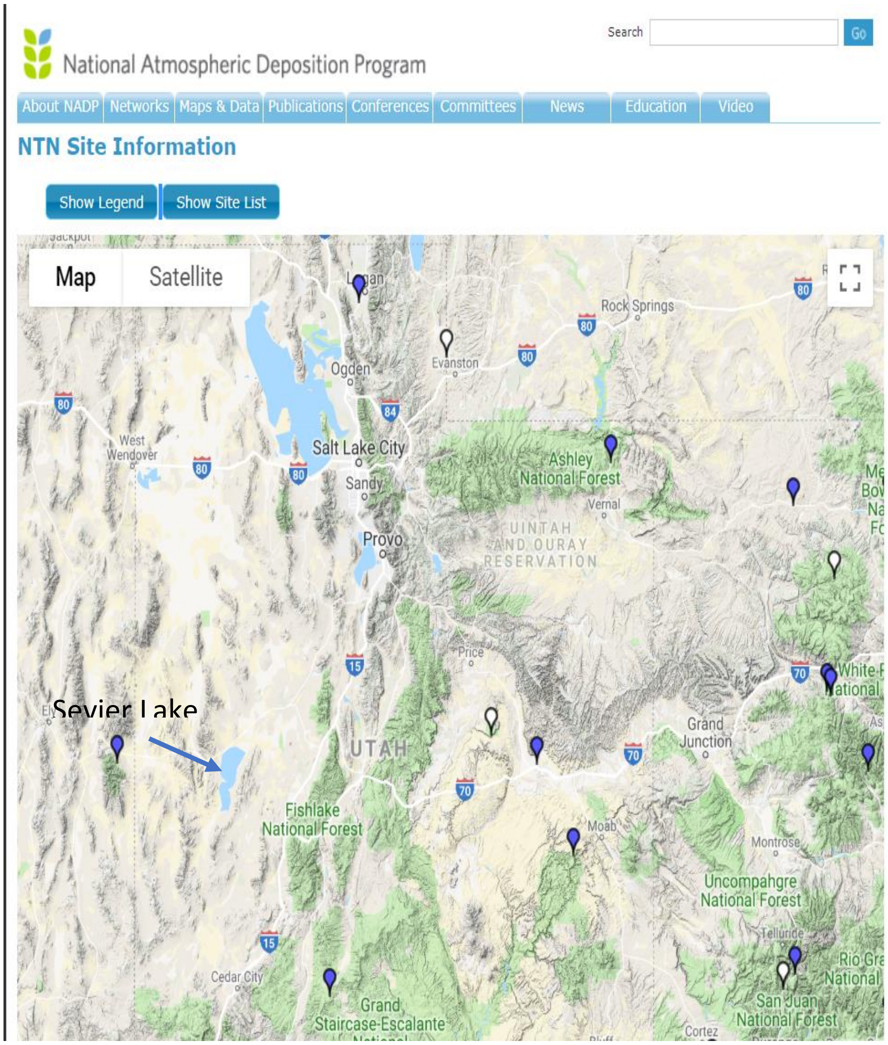

Figure 2. A broader map of Utah which includes portions of Idaho, Wyoming, Colorado, Arizona and Nevada. Note the current location of the NADP sites in Utah (NE Utah, Eastern Uinta Mountains, Green River, Canyonlands NP and Bryce NP).

Figure 3. Photo of dust mobilized from the dry bed of Owens Lake, CA (From Tyler et al. 1997).

Figure 4. Inversion over Salt Lake Valley.

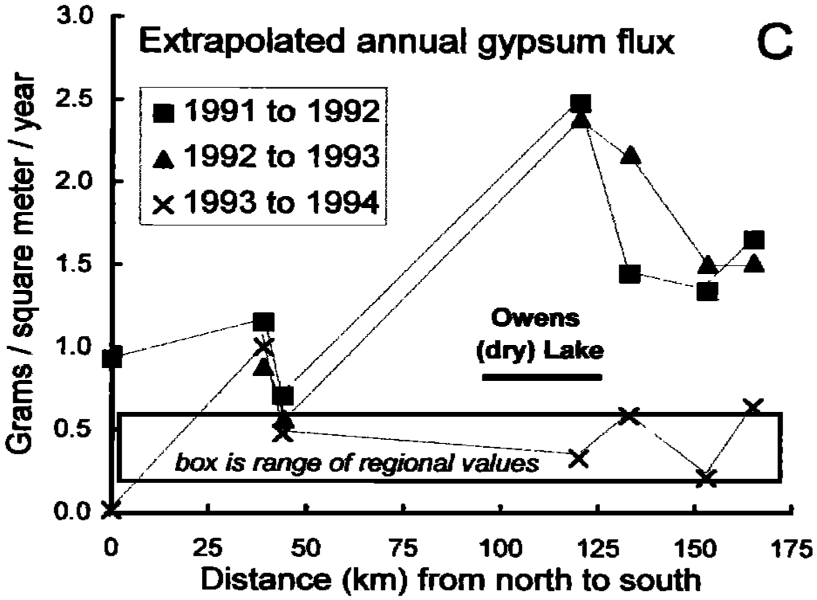

Figure 5. Estimates of gypsum dust flux from Owens Lake, CA. Note elevated concentrations extend at least 50 km from the Source. From Reheis (1997).

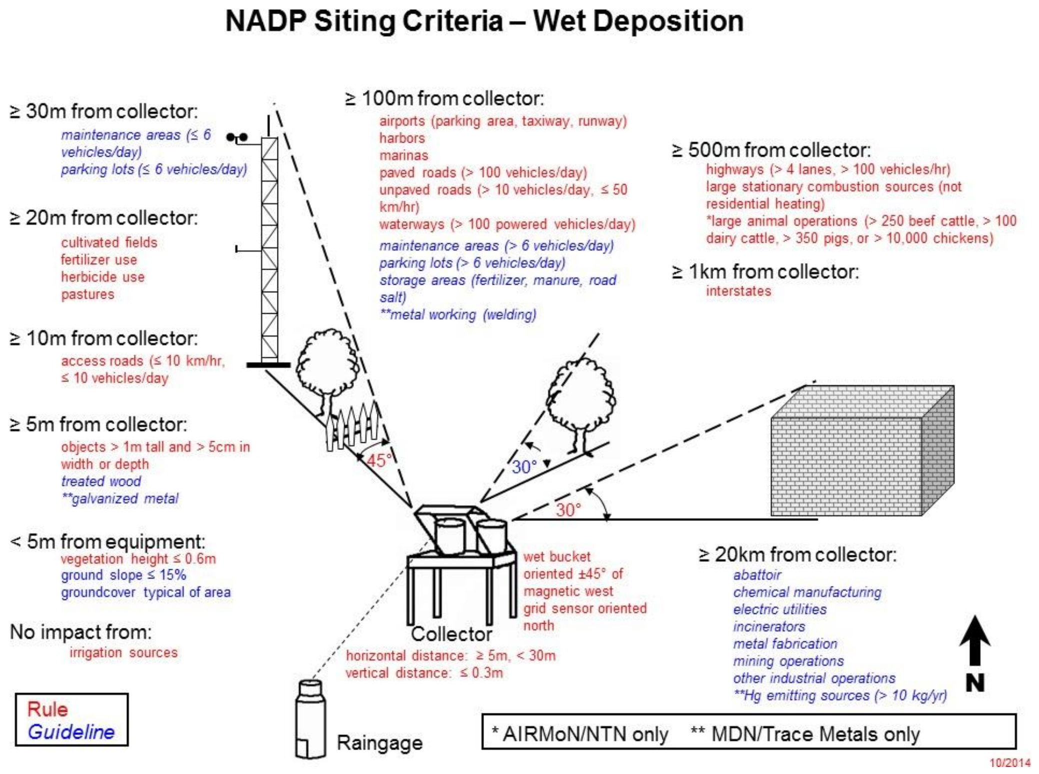

Figure 6. NADP general siting criteria for wet deposition sampling site. Note in this design, influence from local sources is intended to be eliminated – providing only the measurement of regional rain events.

Objectives

The primary objective of the atmospheric deposition project is to provide quantitative estimates of wet and dry deposition to the surface of Utah Lake. Toward this goal sub-objectives include adopting or adapting the most appropriate samplers utilized in the current literature. This will include:

1. The use of a small amount of water in the dry deposition bucket (Zobrist et al. 1993) as it is important to consider a similar surface as the lake,
2. the current USGS method of collecting bulk atmospheric deposition samples (Rheis and Kihl 1995),
3. A modification of the Zobrist method to include a small-mesh screen to capture insects and other debris,
4. Select sites that adhere to NADP protocol (as is currently being followed on three of the sample sites, Figure 6),
5. Exercise the NADP option of identifying important local sources, including urban construction sites, intense agricultural sites, tracking regional sources such as Sevier Lake (i.e. specific research questions, Table 1),
6. Place a sampler near the center of the lake to determine the appropriate attenuation equation for dust or rain-delivered nutrients to the lake, and
7. Provide estimates of nutrient recycling from insect emergence and subsequent deposition.

Hence, as agriculture, road construction and dense urbanization exist and will continue to increase immediately adjacent to Utah Lake, and as an estimated maximum of 6000 tons of midges emerge, breed and return at least some carcasses to the lake per year, this sampling strategy is intended to provide multiple sources of nutrient deposition, as well as from samplers that adhere to NADP's more strict guidelines. In this manner, several samplers will continue to be placed at locations immediately adjacent to the lake's shoreline. As Cole et al. (1990) points out and as our observations suggest, these sources may contribute significantly to a lake's nutrient budget.

Proposed Methods

The NADP does not currently identify a dry deposition protocol. However, as described above, different methods have been adopted to answer different research questions and obtain different types of chemical or physical data. Therefore, we are proposing a suite of sampling strategies that should help determine the most appropriate method(s) to address our research questions.

a. Continue using a small amount of water in the dry deposition bucket (Zobrist et al. 1993, Anderson and Downing 2006), a technique justified in that: "In contrast to solid surrogate surfaces, water exhibits the following advantageous properties: low and constant surface resistance, high sticking coefficient for aerosols, and predictable sorption behavior for gases. Consequently, the deposition rates measured to the wet surface are generally higher, by up to a factor of 4 for NH_4^+, Cl^-, NO_3^- and SO_4^{2-}, than those to a dry surface… The sampling method also allows tracing of regionally and locally emitted atmospheric pollutants."
b. Test the placement of marbles in the bottom of sampling pans (USGS; as has been used by Rheis (1997) and Rheis and Kihl (1995) and is currently being used on Great Salt Lake, personal observations). This type of sampler collects the compartment known as "bulk deposition" (Rheis 1997, Amodio 2014) and is less labor and equipment intensive than other methods. Briefly, "the trap consists of a coated angel food cake pan, or similar, painted black on the outside and mounted on a post about 2 m above the ground. Glass marbles rest on a circular piece of galvanized hardware cloth, which is fitted into the pan so that it rests 3-4 cm below the rim. "The 2-m height eliminates most saltating sand-sized particles. The marbles simulate the effect of a gravelly fan surface and prevents dust that has filtered or washed into the bottom of the pan from being blown away" (Rheis 1997). It should be noted that this 2 m height specification was unique to Owens Lake research where high groundwater is believed to bring additional salts to the surface where they crystallized upon desiccation. The USGS sampler located on the Antelope Island causeway is approximately 1.5 m above the ground level.
c. A modification of our current dry deposition protocol whereby we include placing a bowl-shaped screen approximately 10 cm below the surface of the rim and the screen is comprised of 500 um nylon mesh (standard macroinvertebrate sampling mesh size), to filter out insect and plant debris. The bottom of the bucket would still contain approximately 2 L of distilled water to facilitate catchment of the aerosols. In this way we could accurately measure deposition from wind events while isolating (for separate measurement) the controversial contamination from insect emergence or plant parts. This design has the disadvantage of not being in direct contact with a wet surface (Anderson and

Downing 2006). Even though the Science Panel has mixed feelings about how to account for the very real phenomenon of insect emergence, followed by return of an estimated 10% to 70% of the biomass to the lake surface (analogous to nutrients recycling from sediment), the sheer numbers and biomass of midges residing in the lake warrants an accounting of this phenomenon. We also believe it would be important to deploy emergent traps and in-fall deposition traps in a series of transects extending lake-ward and inland, respectively from the shoreline. Limited literature exists on this subject and this could be an important variable in determining the nutrient budget for the lake. However, monetary constraints may force the delay of this project until 2020. Collaboration between the WFWQC and the Utah Lake Science Panel is a potential approach toward this goal.

d. In addition, we are gaining permission for Utah State Parks to place a platform in the open water of Utah Lake. This will inform the long-term controversial question of the appropriate attenuation model that describes the potential decline of deposition rates as airborne contaminants move across the lake surface. This will provide particular insight into loadings from smog during temperature inversions as well as high wind events and insect movement. The sampler will consist of the wet and dry design. Perhaps most importantly, this will address the question of what is the appropriate decay function model to be used across the lake surface. Additionally, this will elucidate the importance of numerous roadways and agricultural fields adjacent to the lake, but which presently are suggested to be eliminated from the sampling design in accordance with the rural NADP protocols – or because they are suspected to be of minimal consequence.

At this point, we feel that elimination of the mix of heavily urbanized and continued urbanization (construction) within the nearfield watershed, intensive agricultural use, as well as regional dust storms from Sevier Lake, would ignore the measurement of significant urban and rural sources of nutrients that may reach the lake as well as far across the lake surface. In fact, the NADP narrative for site design adds that such specifications are:

> “designated as Guidelines. These criteria are recommendations based on scientific judgment. Due to practical siting considerations and research goals, it may not be possible for sites to meet one or more of these criteria. Failure to meet these criteria does not prohibit a site from either joining, or remaining in an NADP network. Again, the extent of the departure from these criteria may designate the site as *Research/Provisional*.”

While the rules for ammonia deposition specifies that the height of the sampler be 2 m above the ground and that for measuring mercury deposition specifies a minimum of 6 m above the ground, the design for the wet deposition sampler has no height specification (Figure 1). It only mentions in the narrative that the sampler should be 1 to 2 m above the ground. Based on this information, our current design complies with our research goals and is in accordance with NADP specifications. Nevertheless, three of the five collectors around Utah Lake currently comply with the NADP siting criteria of the samplers (Figure 6); as the slight adjustments were made for the 2018 sampling year to move the samplers further away from roads that ran along the lake), the other two samplers are adjacent to agricultural and urbanized areas that reach within 100 m of the lakes edge on the north and west side of Utah Lake. Perhaps the only exception to the NADP siting protocols is that that the solar panel is now mounted on the table (rather than on a post extending approximately 2 m above the platform) and is approximately 10 cm lower than the top of the sample collecting buckets. We believe that this recommendation (referring to galvanized steel in Figure 1) is in reference to the original mission of the NADP, which is reducing the potential for collecting traces of the common metals and ions and Hg, that have the potential for leaching from metal components. In our case, collection of P, nitrate and ammonia is the singular goal of this project and galvanized and stainless-steel structures are not expected to leach nutrients.

Sample analysis

Samples will be analyzed in the BYU Environmental Analysis Lab. This lab is equipped with an IC and follows EPA protocol for preparation of standards, blanks and determining MDLs.

Quality Assurance

A Quality Assurance Project Plan is currently being prepared for this project. This Plan will be finalized in consideration of protocols and suggestions offered by the Science Panel and other reviewers.

Literature Cited

Ahn, H., and James, R. T. (2001). "Variability, uncertainty, and sensitivity of phosphorus deposition load estimates in South Florida." Water, Air, & Soil Pollution, 126(1), 37-51.

Amodio, M. S. Catino, P. R. Dambruoso, G. de Gennaro, A. Di Gilio, P. Giungato, E. Laiola, A. Marzocca, A. Mazzone, A. Sardaro, and M. Tutino. 2014. Atmospheric Deposition: Sampling Procedures, Analytical Methods, and Main Recent Findings from the Scientific Literature. Advances in Meteorology. Vol. 2014, Article ID 161730, http://dx.doi.org/10.1155/2014/161730

Anderson, K. A., and Downing, J. A. (2006). "Dry and wet atmospheric deposition of nitrogen, phosphorus and silicon in an agricultural region." Water, Air, & Soil Pollution, 176(1), 351-374.

Balestrini, R., L. Galli, and G. Tartari, "Wet and dry atmospheric deposition at prealpine and alpine sites in Northern Italy," Atmospheric Environment, vol. 34, no. 9, pp. 1455–1470, 2000.

Bristow, C. S., K. A. Hudson-Edwards, and A. Chappell (2010), Fertilizing the Amazon and equatorial Atlantic with West African dust, Geophys. Res. Lett., 37, L14807, doi:10.1029/2010GL043486.

Cole, J. J., N. F. Caraco and Gene E. Likens. 1990. Short-range atmospheric transport: A significant source of phosphorus to an oligotrophic lake. Limnol. Oceanogr. M(6), 1990, 1230-1237.

Dreyer, J., P. A. Townsend, J. C. Hook III, D. H. Oekman, M. J. Vander Zanden, And C. Gratton. Quantifying aquatic insect deposition from lake to land. 2015. Ecology, 96(2): 499–509.

Durbin, T. D., R. D. Wilson, J. M. Norbeck, J. W. Miller, T. Huai, and S. Rhee. Emissions of Ammonia from Light-Duty Vehicles. https://www3.epa.gov/ttn/chief/conference/ei10/ammonia/durbin.pdf

Gillette D., D. Ono and K. Richmond. 2004 M. D. A combined modeling and measurement technique for estimating windblown dust emissions at Owens (dry) Lake, California. Journal of Geophysical Research, Vol. 109, F01003, doi:10.1029/2003JF000025

Gray, L. J. 1989. Emergence Production and Export of Aquatic Insects from a Tallgrass Prairie Stream. *The Southwestern Naturalist.* Vol. 34, No. 3: 313-318

Loye-Pilot and J. M. Martin. 1996. Impact of Desert Dust Across the Mediterranean, Edited by S. Guerzoni and S. Chester, Kluwer Academic Publishers, Dordrecht, The Netherlands,

Morales-Baquero, R., E. Pulido-Villena &I. Reche. 2013. Chemical signature of Saharan dust on dry and wet atmospheric deposition in the south-western Mediterranean region. https://doi.org/10.3402/tellusb.v65i0.18720

Reheis, M. C. 1997. Dust deposition downwind of Owens (dry) Lake, 1991-1994: Preliminary findings J. Geophysical research. 102, NO. D22, P. 25,999-26,008

Reheis, M.C. and R. Kihl 1995. Dust deposition in southern Nevada and California, 1984–1989: Relations to climate, source area, and source lithology. Journal Geophysical Research: Atmospheres: https://doi.org/10.1029/94JD03245

Reheis, M. C., J. R. Budahn, P. J. Lamothe, R. L. Reynolds. 2009. Compositions of modern dust and surface sediments in the Desert Southwest, United States. Journal of Geophysical Research: Earth Surface, Volume 114, Issue F1

Remer, L. A., Y. J. Kaufman, D. Tanré, S. Mattoo, D. A. Chu, J. V. Martins, R.-R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, *and* B. N. Holben. The MODIS aerosol algorithm, products and validation. Journal Atmospheric Sciences. https://doi.org/10.1175/JAS3385.1

Tyler, S.W., S. Kranz, M.B. Parlange, J. Albertson, G.G. Katuld , G.F. Cochranb , B.A. Lylesb , G. Holdere 1997. Estimation of groundwater evaporation and salt flux from Owens Lake, California, USA. Journal of Hydrology 200: 110–135. Version 1.9

Winter, J.G., P. J. Dillon, M. N. Futter, K. H. Nicholls, W. A. Scheider and L. D. Scott 2002. Total Phosphorus Budgets and Nitrogen Loads: Lake Simcoe, Ontario (1990 to 1998). Journal of Great Lakes Research 28, (3), 301-331.

Yu, H., et al. (2015), The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations, Geophys. Res. Lett., 42, 1984–1991, doi:10.1002/2015GL063040.

Zobrist, J., Wersin, P., Jaques, C. L. Sigg and W. Stumm. 1993. Dry deposition measurements using water as a receptor: A chemical approach. Water Air Soil Pollut (1993) 71: 111. https://doi.org/10.1007/BF00475515

The active surface of the lake (Owens) is about 280 square kilometers. Assuming a density of 2 grams per cubic centimeter for the dust, a layer only 150 microns thick could **produce the dust cloud that extends over the entire affected area. A wind of 25 meters** per second (55 mph), could replenish the entire cloud every 3 hours. Thus about 7 tons of material would be removed each second. Sustained for 24 hours, such a wind would erode 0.12 centimeters of sediment, a thickness small compared to that of the dessication crust that overlies the lake bed.