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Evaluating Cyanotoxins in Surface Water and Aerosols Near Utah Lake

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EVALUATING CYANOTOXINS IN SURFACE WATER AND AEROSOLS NEAR
UTAH LAKE

by

Dylan R. McPeake

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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2025

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ABSTRACT

Evaluating Cyanotoxins in Surface Water and Aerosols near Utah Lake

by

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Utah State University, 2025

Major Professor: Sierra Young, Ph.D.
Department: Civil and Environmental Engineering

Utah Lake is a freshwater lake near Provo in Utah County, Utah. It is the third-largest lake in Utah and serves important recreational and commercial roles for surrounding communities. From June to October, much of the lake is infested with cyanobacterial harmful algal blooms (cHABS), which can pose a public health threat if exposure occurs. Various government agencies routinely monitor cHABS in the water and issue warnings and closings to the public for swimming and other recreational activities when necessary. However, as observed in other lakes containing cHABS, cyanobacteria can aerosolize and pose a threat to humans in the surrounding areas through inhalation, a process that is not currently monitored or considered. This study aimed to characterize the potential presence of cyanotoxins in aerosols near cHABS in Utah Lake through a combination of coordinated water and air sampling, as well as implementing an unoccupied vehicle (UV) to improve water sample collection efficiency. This study was conducted at two separate sites in the Summer of 2024: Lincoln Marina (July 8th to 11th, 2024) and Utah State Lake Park (August 12th to 15th, 2024). Water cHAB samples were collected using both traditional grab sampling and composite samples

collected by a robotic surface UV to measure the amount of cyanotoxins in the water. Water samples were taken once a day, around noon, at three grab sample sites and one general area for composite samples. Air samples were collected onto filters using nine low-volume air samplers running 8-12 hours per day over four days. Water sample preparation and analysis for microcystins were done according to the solid phase extraction (SPE) and liquid chromatography/tandem mass spectrometry (LC/MS/MS) method by the U.S. Environmental Protection Agency (EPA). This method was modified for the extraction and analysis of air filters. Air samples at Utah Lake contained cHABs in detectable concentrations similar to other studies reported in the literature. Wind speed and direction, as well as water agitation, were identified as the major contributing factors to cHAB aerosolization. These findings highlight the need for more research and monitoring of airborne cyanotoxins to better understand the potential health risks for people near Utah Lake.

(166 pages)

PUBLIC ABSTRACT

Evaluating Cyanotoxins in Surface Water and Aerosols near Utah Lake

Dylan R. McPeake

Utah Lake is a freshwater lake in Utah County near Provo, Utah. It is the third-largest lake in Utah and is important for recreation and local businesses. However, from June to October, the lake often has cyanobacteria harmful algal blooms (cHABs), which contain a toxin called cyanotoxin. These toxins can be dangerous to people who come into contact with the water. Government agencies regularly check for cHABs and warn people when the water is unsafe for activities like swimming. Collecting water samples to test for cHABs can be risky because it can possibly result in direct contact with the contaminated water. In addition, it is possible for the cyanotoxins to become airborne and spread through the air, which could be harmful if people breathe them in. However, monitoring the air for cyanobacteria is not currently done at Utah Lake. This study aimed to discover if cyanotoxins in Utah Lake could become airborne and if using a remote-controlled boat could collect water samples similar to a human. Researchers collected water and air samples at two locations—Lincoln Marina and Utah State Lake Park—during the summer of 2024. Water samples were taken daily around noon using both traditional methods and a robotic boat with a water sampler. Air samples were collected onto air filters using vacuum-based air samplers that ran for 8–12 hours each day. The collected samples were analyzed using a method approved by the U.S. Environmental Protection Agency (EPA). The results confirmed that the robotic boat was effective at collecting water samples. More importantly, researchers found that cyanotoxins were

present in the air near the lake at levels similar to other studies. The study also showed that wind speed, wind direction, and water movement played a big role in spreading the bacteria into the air. These findings highlight the need for more research and monitoring of airborne cyanotoxins to better understand the potential health risks for people near Utah Lake.

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Dylan R. McPeake

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ACRONYMS

ASV	Autonomous surface vehicle
cHABS	Cyanobacterial harmful algal blooms
EDTA	Ethylenediaminetetraacetic acid
ELISA	Enzyme-linked immunosorbent assay
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FFP	Flux Footprint Prediction
HPLC	High-performance liquid chromatography
LC/MS	Liquid chromatography/Mass Spectrometry
LC/MS/MS	Liquid chromatography/tandem mass Spectrometry
LM	Lincoln Marina
MDIC	Maximum daily inhaled concentration
MC	Microcystin
PETG	Polyethylene terephthalate
SPE	Solid phase extraction
UAV	Unoccupied Aerial Vehicle
UCHD	Utah County Health Department
UDDW	Utah Division of Drinking Water
UDEQ	Utah Department of Environmental Quality
UDWQ	Utah Division of Water
ULSP	Utah Lake State Park
USU	Utah State University
USV	Unoccupied Surface Vehicle
UT	Utah
UV	Unoccupied vehicle
UWRL	Utah Water Research Laboratory
WHO	World Health Organization
ZOI	Zone of Influence

CHAPTER 1

INTRODUCTION

Utah Lake is a freshwater lake in the Utah Valley near Provo, Utah County, Utah (40.205723, -111.813698) that sits at an elevation of 1365.5 meters above sea level. Utah Lake is 38.6 kilometers long and 20.9 kilometers wide with a total surface area of 38,445 hectares, making it the third-largest lake in Utah and one of the largest natural freshwater lakes in the western United States. Utah Lake serves an important recreational and commercial role for the surrounding communities, as the lake sees camping, fishing, boating, and picnicking in the summer and hunting, ice fishing, and ice skating in the fall and winter months (Utah Lake Authority, 2024).

However, from June to October, much of Utah Lake is affected by cyanobacteria harmful algal blooms (cHABs). Algal blooms can cause an intense deterioration of the water quality, as the events cause shifts in the pH, eutrophication, stratification, water discoloration, and changes in water transparency (Amorim & Moura, 2021; Lopez et al., 2008). cHABs pose a greater threat than algal blooms because, in addition to the environmental degradation, cHABS contain cyanobacteria, a group of bacteria that produce toxins known as cyanotoxins, which can have negative effects on humans and animals when ingested. The most common cyanobacteria found in Utah Lake is *Microcystis*, which produces the toxin microcystin; Nodularin, another very common cyanobacteria, is not found in Utah Lake (Alsanea, 2018; Li, 2021). The possible side effects from ingesting or direct skin contact with microcystin include abdominal pain, headaches, sore throat, vomiting, nausea, dry cough, diarrhea, skin irritation, eye irritation, illness, gastrointestinal and liver inflammation, liver disease, hemorrhage and

liver failure, pneumonia, dermatitis, and death. Of all the congeners of microcystin, Microcystin-LR (MC-LR) is the most toxic and most common (Arman & Clarke, 2021; Lopez et al., 2008; US EPA, 2024; Utah Department of Environmental Quality, 2025b; Wood & Dietrich, 2011).

Since cHABs can pose a serious threat to humans and animals, various agencies such as the Utah Department of Environmental Quality (UDEQ), particularly the Utah Division of Water Quality (UDWQ) and Utah Division of Drinking Water (UDDW), routinely monitor the cHABs in the water at Utah Lake and issue warnings and lake closings to the public for swimming and other recreational activities whenever the total microcystin concentration is more than eight µg/L (Utah Department of Environmental Quality, 2025a; Utah Division of Water Quality, 2023). However, studies have shown that both cyanobacteria and cyanotoxins can aerosolize and potentially enter humans and animals via inhalation. Aerosolization of cyanotoxins is indirectly estimated by measuring inorganic salts, and both organic and biological materials in lake spray aerosols (Labohá et al., 2023; May et al., 2017; Wood & Dietrich, 2011). It has been found that inhaled or nasally applied microcystins can potentially be 10 times more bioavailable and toxic when compared to the ingestion pathway (Yoshida et al., 1997). Regulatory agencies currently do not monitor the atmosphere for cyanotoxins, meaning people near water bodies when cHABs are present may be unknowingly exposed to cyanotoxins through inhalation.

In addition to the possibility of dangerous levels of cyanotoxins in the air, there is also the concern of exposure to cyanotoxins when taking samples of cHABs. Current UDEQ and UDWQ guidelines dictate that water cHAB samples are to be collected by

dipping a bottle into the subject water from the shoreline or from a boat. While this method is effective, it still possesses the chance that the person conducting the sampling could come into contact with cyanotoxins by accident and become sick if the proper safety precautions are not followed. One way that could allow for water cHAB sample collection but reduce the chance that the sampler would come into contact with cyanotoxins would be to use an unoccupied vehicle (UV) to assist in sample collection (Powers, Hanlon, Grothe, et al., 2018; Powers, Hanlon, & Schmale, 2018). A UV would allow for the collection of samples without the need for a human sampler, except for guiding the boat and removing the sample bottle.

To understand the potential for aerosolization of cyanotoxins during cHABs and develop protocols for utilizing UV for water sampling at Utah Lake, the objectives of this project were to (i) develop a methodology for analyzing microcystins in air samples, (ii) collect and analyze air samples from Utah Lake to determine if microcystins are present in the air at detectable levels, and (iii) build and test an autonomous unoccupied vehicle as an alternative method for collecting cHAB water samples. Accomplishing these objectives requires further exploration into what cHABs are, the biological factors that influence cHAB growth and production, the mechanisms of cyanotoxin aerosolization, air and water cyanotoxin sample collection, air and water cyanotoxin sample analysis, and the usage of UVs for environmental monitoring and sample collection. Chapter 2 details a literature review to the topics of interest, Chapter 3 discusses preliminary studies performed before the main experiment to help solidify the methodology, Chapter 4 details the methodology for conducting the primary study, Chapter 5 presents the results

of the study, Chapter 6 analyzes the results in the discussion, and Chapter 7 concludes this work and lays the groundwork for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Algal Blooms and cHABS

Algae are photosynthetic microscopic organisms found in water bodies (National Institute of Environmental Health Sciences, 2025). An algal bloom occurs when there is a rapid increase in the amount of algae in a body of water; there is no official threshold to the rate at which an algae population grows and reaches bloom status. Cyanobacteria harmful algal blooms (cHABs) are a type of HAB where the main toxin-producing organism growing is cyanobacteria. The most common cyanobacteria found in Utah Lake is *Microcystis* (Alsanea, 2018; Li, 2021). *Microcystis* produces the toxin microcystin, where the most common and most lethal version of the toxin is Microcystin-LR (MC-LR) (US EPA, 2024).

2.1.1. Factors that Affect cHAB Formation and Production

The primary source of cHABs in water bodies is eutrophication, where excessive nutrients such as nitrate and phosphorus enter a body of water, increasing the nutrients available and allowing for the growth of microorganisms that would not normally grow under conditions with less available nutrients. While excess nutrients or nutrient enrichment is the leading cause for the growth of cHABs, many environmental factors can influence how well or fast the cHABs grow, including temperature, light intensity, pH, salinity, ultraviolet radiation, and wind (Boopathi & Ki, 2014). Of the listed factors, temperature is arguably the most influential, as cyanobacteria thrive in higher temperatures, giving them a competitive advantage in hot areas, reducing vertical mixing,

and lowering the nutrients required for cHAB growth (Paerl & Huisman, 2008). Temperature and sunlight also help drive chlorophyll synthesis, which determines how quickly algae can grow and multiply. Given that so many factors influence cHAB growth and production, it is very hard to deterministically or mechanistically model the growth and production of cHABs. This difficulty is the reason why monitoring cHABs through sampling and analysis is an important and active area of work. However, there has been research that shows that microcystin concentrations have a positive correlation with chlorophyll-a (Douglas Greene et al., 2021; Kotak et al., 1995; Oh et al., 2001; Singh et al., 2015; Zhang et al., 2017) and phycocyanin (Francy et al., 2016, 2020; Lehman, 2007; Marion et al., 2012; Smith et al., 2024) concentrations.

2.1.2. Mechanisms of Aerosolization

Cyanotoxins can become bioaerosols when a disturbance or turbulence occurs within the water body, dislodging the cyanobacteria and the cyanotoxin from the water and into the air above through spray aerosols, with the toxin being more likely to aerosolize (Labohá et al., 2023; May et al., 2017; Wood & Dietrich, 2011). The primary way algae cell debris, bacteria, and waterborne toxins can become aerosolized is by a bubble-bursting process that ejects the cyanotoxins from the water with the breaking of waves (Cheng et al., 2007; May et al., 2017; Wiśniewska et al., 2019). Water sports and recreation, such as boating, can cause massive disturbances and waves in the water, further promoting the bubble-bursting and wave-breaking processes (May et al., 2017). However, that is not the only disturbance that can release cyanotoxins from water. Wind speeds above seven m/s can rip cyanotoxin bioaerosols water droplets from the water or cause wave disturbances in a water body (Wiśniewska et al., 2019). Wind speed has also

been shown to be a major driver of general spray aerosol production (Bruch et al., 2021; Markuszewski et al., 2024; Revell et al., 2021; Saliba et al., 2019). It is also possible for bioaerosols containing cyanotoxins to be emitted during storm events due to the splashing of raindrops on the water bodies' surface. The cyanobacteria's size also matters, as smaller particles have a greater potential to become aerosolized. In addition to the events that can eject cyanotoxin bioaerosols from the water, one of the biggest factors influencing the aerosolization of cyanotoxins is the amount of cyanotoxins in the water, which is a direct result of factors such as temperature and sunlight (Wiśniewska et al., 2019).

Once the cyanobacteria become airborne, numerous factors such as air mass advection, wind speed and direction, humidity, temperature, and rainfall can affect the aerosolized cyanobacteria's travel (Lewandowska et al., 2017; Wiśniewska et al., 2019). Air mass advection, the movement of air from one spot to another due to differences in atmospheric values, is a major reason for aerosolized cyanobacteria being transferred from overwater to overland. Wind speed and direction are important for airborne cyanobacteria frequency and play a role in air transport and travel distance. Humidity is an important factor, as different bioaerosols have different humidity tolerances. Cyanobacteria, the focus of this study, can survive in a wide range of humidity but thrive when the humidity is at a high or low extreme (Wiśniewska et al., 2019). Temperature plays a unique role in cyanobacteria aerosolization, as temperatures influence the humidity, evapotranspiration, and air mass advection. As mentioned previously, rainfall can cause the cyanobacteria to aerosolize more due to disturbing the water; however, rainfall can also decrease the amount of aerosolized cyanobacteria in the atmosphere by

wet deposition via washout or rainout. Stressors such as desiccation, atmospheric pollutants, and ultraviolet radiation can also inhabit bioaerosols in the atmosphere. Atmospheric and weather conditions must be recorded to understand the aerosolized cyanobacteria fully. Understanding the concentrations of cyanotoxins in the water is paramount for understanding the cyanotoxin concentrations in the air, so the collection and analysis of water samples should be sampled in conjunction with air samples.

2.2 cHABs Field Sample Collection Methods

2.2.1. Water Sample Collection

The United States Environmental Protection Agency (EPA) has outlined its recommended methodology for collecting water samples to analyze microcystins and Nodularin in freshwater (Shoemaker et al., 2017). The EPA recommended using amber glass or polyethylene terephthalate (PETG) bottles for water sample collection to protect samples from ultraviolet light. Collected samples are to be 100 mL in volume, and the bottles are prepared using preservative reagents of 7.75 g/L of Trizma, 2.0 g/L 2-Chloracetamide, and 0.35 g/L Ethylenediaminetetraacetic acid (EDTA) trisodium salt; the preservatives allow the samples to be held for 28 days. Once collected, the samples must be chilled in shipment, never exceeding 10 °C, and stored in a freezer below 6 °C until sample analysis.

The EPA's methodology does not detail the logistics of sampling: where to sample, how often to sample, how many samples must be taken, etc. Sampling frequency is dependent on whether one wants to track cyanotoxin concentration changes throughout the day. Possible frequencies include every 4-6 hours or multiple times a day for a shorter time span, such as a week (Backer et al., 2008; Wood et al., 2011; Wood & Dietrich,

2011) or weekly, if one wants to track changes over a season (Banerji et al., 2018). The water samples can either be taken near the shoreline (Wood & Dietrich, 2011) or anywhere on the water body using a boat (Banerji et al., 2018). Regardless of where the water samples are taken relative to the shore, there are normally multiple sampling sites that are well-defined, sufficiently spaced, and constantly revisited. The water samples are collected from the surface of the water, typically within the first five to 30 centimeters (Banerji et al., 2018; Langley, 2019; May et al., 2017; Plaas et al., 2022; Turner et al., 2018). While not required, Turner et al. (2018) recommended to take water samples from the “scummiest” spots to have samples representative of the worst possible conditions. Water samples are typically collected into a carboy first and mixed before being transferred to smaller bottles (Banerji et al., 2018; May et al., 2017; Plaas et al., 2022; Shi et al., 2023). Samples are best taken in triplicate to test for precision (Langley, 2019). In conjunction with the physical water samples, sondes or some other water quality sensors (such as a fluorometer) are used to capture water quality data (Banerji et al., 2018; Labohá et al., 2023; Langley, 2019; Plaas et al., 2022; Shi et al., 2023).

2.2.2. Air Sample Collection

There are no standards for sampling cyanotoxins in the air. As such, the methodology used to measure aerosolized cyanotoxins differs between studies (Wiśniewska et al., 2019). Table 1 summarizes the common themes among studies.

The primary samplers used to collect cyanotoxin aerosols are vacuum pumps, including high-volume samplers with flow rates greater than 300 L/min (Backer et al., 2008, 2010; Cheng et al., 2007; Labohá et al., 2023; Plaas et al., 2022; Wood & Dietrich, 2011) and low-volume samplers with flow rates less than 10 L/min (Carter, 2022;

Langley, 2019; Lewandowska et al., 2017; May et al., 2017; Metcalf et al., 2023; Murby & Haney, 2015; Shi et al., 2023; Wiśniewska et al., 2022; Wood & Dietrich, 2011). It should be stated that flow rates above 30 L/min can cause stress to the cyanobacteria and affect collected samples (Wiśniewska et al., 2019). Inside the samplers, filters are the most common method used to capture the aerosols. Commonly used filters include quartz fiber (Labohá et al., 2023; Plaas et al., 2022), glass fiber (Carter, 2022; Langley, 2019; Shi et al., 2023; Wood & Dietrich, 2011), polytetrafluoroethylene (PTFE) (Wood & Dietrich, 2011), and membrane (Murby & Haney, 2015). In addition to filters, cyanotoxin aerosols have also been captured in Erlenmeyer flasks (Metcalf et al., 2023). Some studies have also implemented PM_{2.5} impactor heads to help better collect particulate matter at 2.5 micrometers or less (Cheng et al., 2007; Plaas et al., 2022; Shi et al., 2023).

The locations of the air samplers vary between studies, between the samplers being stationed on the land/shore (Backer et al., 2008, 2010; Cheng et al., 2007; Labohá et al., 2023; Langley, 2019; Plaas et al., 2022; Trout-Haney et al., 2020; Wood & Dietrich, 2011), stationed over the water (Carter, 2022; Metcalf et al., 2023; Murby & Haney, 2015), stationed on the shore and over the water (Lewandowska et al., 2017; Shi et al., 2023; Wiśniewska et al., 2022), or sampling in a laboratory experiment (May et al., 2017; Murby & Haney, 2015). For the studies, some opted to use multiple samplers, ranging from two to 10 samplers (Backer et al., 2008, 2010; Carter, 2022; Cheng et al., 2007; Lewandowska et al., 2017; Murby & Haney, 2015; Plaas et al., 2022; Shi et al., 2023; Trout-Haney et al., 2020; Wiśniewska et al., 2022; Wood & Dietrich, 2011), while others opted to use a single sampler (Labohá et al., 2023; Langley, 2019; May et al., 2017; Metcalf et al., 2023). Sampling time and frequency also differ between studies,

with some sampling less than two hours (Lewandowska et al., 2017), some sampling between two and 12 hours (Carter, 2022; Langley, 2019; Murby & Haney, 2015; Plaas et al., 2022; Wood & Dietrich, 2011), and others sampling more than 24 hours straight (Labohá et al., 2023; Shi et al., 2023; Trout-Haney et al., 2020; Wood & Dietrich, 2011). Most of the listed studies collect an integrated sample over multiple days. Air samplers can only produce a single air sample, but it is possible to get triplicate samples by placing three air samplers in close vicinity to where they are collecting a similar sample but not interfering with one another; this can be as short as two meters (Carter, 2022; Trout-Haney et al., 2020; Wood & Dietrich, 2011). Labohá et al. (2023) also include a device in the water that constantly simulates human activity or disturbance underneath the sampler. Weather plays a major factor in cyanobacteria aerosolization and travel, and should also be considered (Carter, 2022; Langley, 2019; Lewandowska et al., 2017; Shi et al., 2023; Trout-Haney et al., 2020; Wiśniewska et al., 2019, 2022; Wood & Dietrich, 2011).

While there are significant differences between studies when discussing air sampling methods, most studies seem to agree that the samples should be collected onto some type of filter, samplers are best placed on the shore, and multiple samplers should be used. Given the almost even split between high-volume and low-volume samplers, a preliminary study should be conducted to help determine the appropriate sampler of the two.

Table 1*Summary of cyanotoxin air sampling methodology differences*

Study	Sampler Type		Filter Types	Location	Number of Samplers	Length of Sampling
	High-Volume (>300 L/min)	Low-Volume (<10 L/min)				
Backer et al., 2008	X		X X		X	X
Backer et al., 2010	X		X X		X	X
Carter, 2022		X X		X	X X	
Cheng et al., 2007	X		X X		X	X
Labohá et al., 2023	X	X		X	X	X
Lewandowska et al., 2017	X		X X X		X X	
Langley, 2019	X	X		X	X	X
May et al., 2017	X		X	X X		X
Metcalf et al., 2023	X		X	X X		X
Murby and Haney, 2015	X		X	X X	X	X
Plass et al., 2022	X	X	X		X X	
Shi et al., 2023	X	X	X X		X	X

Study	Sampler Type	Filter Types	Location	Number of Samplers	Length of Sampling
Trout-Haney et al., 2020	High-Volume ($>300 \text{ L/min}$)	Quartz	Shore	Single	<2 hours
Wiśniewska et al., 2022	Low-Volume ($<10 \text{ L/min}$)	Glass	Water	Multiple	2-12 hours
Wood and Dietrich, 2011		PTFE	Lab	X	>24 hours
		Membrane			Unspecified
		Unspecified			

2.3 cHABs Laboratory Analysis Methods

2.3.1. Water Sample Analysis

For water samples, there are methods recommended by the U.S. EPA: enzyme-linked immunosorbent assay (ELISA) (Method 546) (Wendelken et al., 2016) and solid phase extraction (SPE) and analysis of the extract by liquid chromatography/tandem mass Spectrometry (LC/MS/MS) (Method 544) (Shoemaker et al., 2017). The ELISA method is commonly used by agencies for analysis of total microcystins, cylindrospermopsins, saxitoxin, and anatoxin-a. The SPE and LC/MS/MS method provide analysis of individual microcystin congeners and lower detection limits for all the congeners but is more labor intensive. The SPE and LC/MS/MS method consists of three different

sections: sample preparation through filtration, SPE, and extraction analysis using LC/MS/MS. This method is capable of handling general and highly concentrated samples, although the sample preparation steps are different. While this methodology is for water samples only, it is a method that is certified by the US EPA and is useful for analyzing cyanotoxins present in the water.

2.3.2. Air Sample Analysis

Similar to the collection of cyanotoxin aerosols, there are no standards for analyzing cyanotoxins in the air; the methodology of analyzing aerosolized cyanotoxins differs between studies (Wiśniewska et al., 2019). Table 2 summarizes the common themes among studies.

There are two main methods to analyze microcystins: ELISA (Backer et al., 2008, 2010; Carter, 2022; Cheng et al., 2007; Langley, 2019; Murby & Haney, 2015; Wood & Dietrich, 2011) and LC/MS (Backer et al., 2008, 2010; Labohá et al., 2023; May et al., 2017; Plaas et al., 2022; Shi et al., 2023; Wood & Dietrich, 2011). The biggest difference between ELISA and LC/MS is that ELISA shows total microcystin concentrations, while LC/MS allows users to see the concentrations of different microcystin congeners in addition to the total microcystin concentration. It should be noted that Wood & Dietrich (2011) generally showed that while the LC/MS produced lower cyanobacteria microcystin concentrations compared to the ELISA method, both the ELISA and LC/MS produced comparable data.

Most differences between studies come from how to prepare or extract air samples for ELISA or LC/MS analysis. The most common preparation step shared by studies is cutting up the filters (Backer et al., 2008, 2010; Carter, 2022; Cheng et al.,

2007; Gambaro et al., 2012; Labohá et al., 2023; Langley, 2019; Plaas et al., 2022; Wood & Dietrich, 2011). After cutting the filters, the possible preparation steps vary, even between studies using the same analysis method. Possible preparation steps include sonicating the samples (Gambaro et al., 2012; Plaas et al., 2022; Shi et al., 2023; Wood & Dietrich, 2011), centrifuging the samples (Carter, 2022; Langley, 2019; Murby & Haney, 2015), spinning the samples (Backer et al., 2008, 2010; Cheng et al., 2007), filtering the samples (Gambaro et al., 2012; Plaas et al., 2022; Shi et al., 2023), employing freeze-thaw cycles to rupture cells (Carter, 2022; Langley, 2019; Murby & Haney, 2015; Shi et al., 2023), drying or evaporating samples under Nitrogen, and then reconstituting or resuspending the evaporated samples in water or methanol (Gambaro et al., 2012; Labohá et al., 2023; Plaas et al., 2022; Shi et al., 2023; Wood & Dietrich, 2011), and concentrating the sample five times (Carter, 2022; Langley, 2019; Murby & Haney, 2015). Metcalf et al. (2023) submerged filters in 20 mL of methanol and then 20 mL of 20 mM hydrochloric acid. Contrary to these previous studies, May et al. (2017) introduced the aerosols generated in a lab study into a time-of-flight single particle mass spectrometer; they didn't directly analyze for microcystins.

When considering the cyanotoxin analysis for both water samples and air samples, it is possible to use the same EPA LC/MS/MS methodology for both sample types if modifications are made to the methodology to support air samples (Shoemaker et al., 2017).

Table 2*Summary of cyanotoxin air sample analysis methodology differences*

Study	Analysis Methods		Preperation & Extraction Steps								
	ELISA	LC/MS	Cut up Filters	Sonicated	Centrifuged	Spun/Rotated	Filtered	Freeze-Thaw Cycles	Dried under N ₂	Reconstituted or Resuspended	Concentrated
Backer et al., 2008	X	X	X			X					
Backer et al., 2010	X	X	X			X					
Carter, 2022	X		X	X				X			X
Cheng et al., 2007	X		X		X						
Gambaro et al., 2012		X	X	X			X		X	X	
Labohá et al., 2023		X	X						X	X	
Langley, 2019	X		X		X			X			X
Metcalf et al., 2023			X								
Murby and Haney, 2015	X				X			X			X
Plass et al., 2022		X	X	X			X		X	X	
Shi et al., 2023		X		X			X	X	X	X	
Wood and Dietrich, 2011	X	X	X	X					X	X	

2.4 Air Sample Concentrations

Table 3 summarizes the concentrations among studies that measured total microcystins in aerosols. All studies provide MC concentrations measured in pg/m³, with the two exceptions of Labohá et al. (2023) and Gambaro et al. (2012), whose concentrations were originally in fg/m³ (their results were converted to pg/m³ to maintain homogeneity with the other results in the table). While the aerosol concentrations were lower when compared to other studies, Labohá et al. (2023) was able to show that the

ratio of aerosol/water concentrations for previous studies were between 10^{-8} to 10^{-13} , which the aerosol/water concentration ratios for their study were as well.

Table 3

Summary of total microcystin air concentrations of previous studies in pg/m³

Study	Location	Microcystin Air Concentration (pg/m ³)
Backet et al., 2008	Michigan, USA	Day 1 Average: 80 ± 90 Day 1 Range: 5 – 319 Day 2 Average: 70 ± 14 Day 2 Range: 20 – 456 Day 3 Average: <LOD Day 3 Range: <LOD
Backer et al., 2010	California, USA	Day 1 Lake 1 Average: 400 ± 750 Day 1 Lake 1 Range: 0.00 – 2900 Day 2 Lake 2 Average: 100 ± 230 Day 2 Lake 2 Range: 0.00 – 800 Day 3 Lake 2 Average: 200 ± 170 Day 3 Lake 2 Range: 0.00 – 400
Carter, 2022	Massachusetts, USA	Walker Pond Average: 91.81 ± 11.46 Walker Pond Range: 57.39 – 165.90 Lower Mill Pond Average: 73.27 ± 8.75 Lower Mill Pond Range: 51.51 – 128.08
Cheng et al., 2007	Michigan, USA	Day 1 Average: 80 ± 90 Day 2 Average: 70 ± 14 Day 3 Average: 0.0 ± 0.0
Gambaro et al., 2012	Venice, Italy	Range: 0.091 – 0.909
Labohá et al., 2023	Czech Republic	Range: 0.057 – 0.415
Langley, 2019	NH/Mass., USA	Range: 0.93 – 3.79
Murby and Haney, 2015	ME/NH/Mass., USA	Range: 13 – 384
Shi et al., 2023	Ohio, USA	Max: 156 Lake Forsyth 12hr Average: 0.73 ± 0.64 Lake Forsyth 12hr Range: 0.14 – 1.62 Lake Forsyth 24hr Average: 0.023 ± 0.005 Lake Forsyth 24hr Range: 0.02 – 0.03 Lake Rotorua 24hr 1: 0.03 Lake Rotorua 4hr: 0.18 Lake Rotorua 24hr 2: 0.9
Wood and Dietrich, 2011	New Zealand	Lake Forsyth 12hr Average: 0.023 ± 0.005 Lake Forsyth 12hr Range: 0.02 – 0.03 Lake Rotorua 24hr 1: 0.03 Lake Rotorua 4hr: 0.18 Lake Rotorua 24hr 2: 0.9

2.5 Usage of Unoccupied Vehicles (UVs) for Water Quality Monitoring

Unoccupied vehicles (UVs) have revolutionized environmental monitoring, as UVs have many advantages over traditional methods, such as real-time data collection, increased versatility and accessibility, cost-effectiveness, and enhanced detection capabilities (Sprincean et al., 2020). When using UVs for water quality monitoring, the two types of UVs one can choose between include unoccupied aerial vehicles (UAVs) and unoccupied surface vehicles (USVs). The difference between UAVs and USVs is that UAVs operate in the air while USVs operate on a surface, particularly water. UVs can either be bought pre-built (Bilyeu et al., 2022; Doi et al., 2017; Ore et al., 2015; Powers, Hanlon, Grothe, et al., 2018; Powers, Hanlon, & Schmale, 2018) or custom-built to meet specifications (Dsouza et al., 2021; Jo et al., 2019; Koparan et al., 2018; Wichlinski, 2021; Wu et al., 2022). Regardless of whether one uses a pre-built or custom UV, advances in 3D printing technologies allow researchers to modify the vehicle to the needed specifications in quick turnarounds by developing light, custom payloads (Bilyeu et al., 2022; Doi et al., 2017; Dsouza et al., 2021; Jo et al., 2019; Koparan et al., 2018; Ore et al., 2015; Powers, Hanlon, Grothe, et al., 2018; Powers, Hanlon, & Schmale, 2018; Wichlinski, 2021; Wu et al., 2022). In addition to sample collection, UVs also implement Global Positioning System (GPS) modules, which not only tell users where the UV is located but also allows for autonomous functionality and provides locations for samples taken (Bilyeu et al., 2022; Doi et al., 2017; Dsouza et al., 2021; Jo et al., 2019; Koparan et al., 2018; Ore et al., 2015; Powers, Hanlon, Grothe, et al., 2018; Powers, Hanlon, & Schmale, 2018; Wichlinski, 2021; Wu et al., 2022).

2.5.1. Unoccupied Aerial Vehicles (UAVs)

UAVs have been used primarily for remote sensing and photogrammetry but have also been used for collecting physical water samples and bioaerosols for water quality analysis. UAVs have given researchers an unprecedented platform to advance spatiotemporal insights without the need for satellites, as they can be focused on specific areas for specific times at whatever resolution one wants or can afford (Manfreda et al., 2018). UAVs allow researchers to collect data related to vegetation, soil moisture content, river systems, flow rates, and many more. However, UAVs do come with their issues. Notably, UAVs can face remote sensing challenges such as image blur from motion, resolution issues due to flying height, and similar issues that satellites face, such as geometric distortion and spectral effects.

For physical sample collection, the methods vary depending on whether one is collecting physical water samples or air samples. For physical water samples, the methods ranged from using a water pump and flexible pipe to collect water samples (Ore et al., 2015) and dipping a bottle or catchment device into the water body from a rope to collect samples (Doi et al., 2017; Koparan et al., 2018). For the water pump methodology, a servo motor was used to change which sampling bottle was being used (Ore et al., 2015). In addition, a flushing system was implemented to help decontaminate the pump and flexible pipe. There were no significant differences between water samples collected using UAVs when compared to water samples collected through more traditional means (Doi et al., 2017; Koparan et al., 2018; Ore et al., 2015). It should be noted that collecting physical water samples is limited by the payload of the UAV, as UAV flight is limited by the payload capacity; this means that UAVs can realistically only collect one to three

water samples per run, depending on the required sample volume. UAVs have a unique capability for collecting bioaerosols, as they allow for bioaerosol collection at heights that are not possible for USVs or shoreside air samplers (such as 10 meters above the ground). A major issue to consider, however, is the air sampler location, as placing the air sampler underneath the drone can cause sample collection interference from propeller downwash; this can be avoided by placing the sampler above the UAV (Bilyeu et al., 2022; Powers, Hanlon, Grothe, et al., 2018). The possible flight times for missions varied depending on the payload of the drone and the battery supplying power, but the flight times generally range between 5 to 20 minutes (Bilyeu et al., 2022; Doi et al., 2017; Koparan et al., 2018; Ore et al., 2015).

2.5.2. Unoccupied Surface Vehicles (USVs)

For water quality, USVs have typically been used to collect water quality parameters, physical water samples, and bioaerosols. Sensors allow for USVs to collect various water quality parameters *in situ* and real-time, such as pH, dissolved oxygen, temperature, pressure, turbidity, phycocyanin, and many others (Dsouza et al., 2021; Jo et al., 2019). This removes the possibility of incorrect measurements in labs if certain parameters change (temperature) or degrade (phycocyanin). The primary method for collecting physical water samples using USVs is to use a water pump (Dsouza et al., 2021; Powers, Hanlon, & Schmale, 2018; Wichlinski, 2021; Wu et al., 2022). There are several ways to approach sampling using a pump, such as sampling into a single bottle one at a time (Dsouza et al., 2021; Wichlinski, 2021), using solenoids to control which sample bottle is filled (Wu et al., 2022), or taking water samples from the same location but at different depths (Powers, Hanlon, & Schmale, 2018). The upside to USVs versus

UAVs for physical sample collection is that USVs tend to have significantly higher payloads than UAVs (i.e., >1 kg vs. 10 kg), meaning a USV can collect more physical samples per run (Bilyeu et al., 2022; Powers, Hanlon, & Schmale, 2018). USVs allow for the collection of bioaerosols over water, something that an onshore sampler could not do. This allows researchers to analyze aerosols over the water for comparison with aerosols over land. Runtimes for USVs vary between models, but they are above the runtimes for UAVs are in the range of 1-3 hours (Dsouza et al., 2021; Powers, Hanlon, Grothe, et al., 2018; Powers, Hanlon, & Schmale, 2018; Wichlinski, 2021; Wu et al., 2022).

2.5.3. UAVs vs. USVs for Environmental Sampling

Nguyen et al. (2024) detailed the pros and cons of using UAVs vs. USVs for water quality sampling; Table 4 summarizes the pros and cons between UAVs and USVs. The two pros of UAVs compared to USVs are the capability of traveling at faster speeds and greater accessibility due to the ability to fly. The three cons of UAVs compared to USVs are shorter endurance or runtimes, smaller payload capacities due to size, and potentially greater regulation due to occupying Federal Aviation Administration (FAA) airspace. The three pros of USVs compared to UAVs are longer endurance or runtimes, higher payload capacity since they aren't restricted by flight, and the potential to collect *in situ* or on-site data. The two cons of USVs compared to UAVs are slower speeds and limited accessibility, as they can only travel on a surface. In addition to the mentioned pros and cons, a USV is more likely to survive a failure than a UAV, as a USV can float and be rescued. Given the previously discussed studies, using a USV would be more beneficial than using a UAV due to the longer runtimes, the ability to take more water samples than UAVs, fewer restrictions, and the greater potential for recovery should

something go awry. There were modes of operation used with UAVs that could be carried over to the USV for physical water sampling, such as using a servo motor to change bottles and having a flushing system to decontaminate the tube collecting the samples (Ore et al., 2015). Concerning the types of samples to take, physical water samples and water quality parameters seem like the best ones to take. Both the microcystin concentration from the water samples and the parameters from the water quality data give a strong overall picture of the amount of microcystins in the water and the conditions influencing them. For air samples, collecting them on land near the shore appears to be the best practice. While having air samples over the water or in the atmosphere could be useful, sampling a sufficient air volume during USV operation remains challenging.

Table 4

Summary of the pros and cons of using USVs and UAVs for water quality monitoring

UAVs		USVs	
Pros	Cons	Pros	Cons
Faster travel speeds	Shorter endurance	Longer endurance	Slower speeds
Greater accessibility	Smaller payload capacity	Higher payload capacity	Limited accessibility
	Potentially greater regulation	Potential to collect <i>in situ</i> data	

Note. Adapted from *Towards Autonomous, Optimal Water Sampling with Aerial and Surface Vehicles for Rapid Water Quality Assessment* (p. 92) by Nguyen et al., 2024, St. Joe Joseph, Michigan: American Society of Agricultural and Biological Engineers.

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CHAPTER 3

PRELIMINARY STUDIES

3.1 Pilot Air Sampling Study

This pilot air sampling study was conducted to test whether the later described methodology for collecting and analyzing microcystins in the air worked before conducting a robust field campaign the following summer. The pilot study and the following methodology were devised from previous studies detailed in the Chapter 2 Literature Review. This pilot study also intends to determine whether the low-volume or high/mid-volume air samplers are better for this sampling aerosolized microcystins at Utah Lake.

3.1.1. Methods

3.1.1.1. Site/Sampler Location and Timeline

A pilot study was conducted at Lincoln Beach Marina in Spanish Fork, Utah, from Thursday, October 5th, 2023, to Friday, October 6th, 2023, to test the sampling methodology. The Utah Division of Water Resources (UDWR) and Utah County Health Department (UCHD) issued a warning advisory for Utah Lake the week of September 27, 2023, and the week of October 16, 2023, but there is no information if there was a warning advisory during the week of October 1st, 2023 (Utah Division of Water Quality, 2023). It is unknown if this means they didn't sample during the week of October 1st, 2023, or did sample but didn't have results to report. Lincoln Marina (Figure 1) was chosen due to it being a historic hot spot of HAB activity at Utah Lake with heavy recreational traffic (Randall et al., 2019; Tate, 2019).

Figure 1

(Left) Zoomed out view of showing sampling locations at Lincoln Marina Beach, Utah Lake, and (Right) Zoomed in view showing sampling locations at Lincoln Marina Beach, Utah Lake



Note. The green marker is for water samples, while the red marker corresponds with the air samplers (Google Earth, 2025).

3.1.1.2. Weather

Meteorology data for this sampling campaign were collected from the MesoWest station KPVU, Provo Municipal Airport, from Thursday, October 5th, 2023, to Friday, October 6th, 2023. The start, end, and elapsed times for each sampling day can be seen in Table 5; only meteorological data during the sampling period were used. The 2-day average station pressure was 654 mmHg, the average temperature was 15.6 °C, and the average relative humidity was 57.0%; daily temperature and relative humidity data can be seen in Table 6. A time series of wind data can be seen in Figure 2, and a wind rose for October 5th and October 6th can be seen in Figure 3 and Figure 4, respectively. On October 5th, the average wind speed was 2.50 m/s from the west, and on October 6th, the

average wind speed was 2.18 m/s from the southwest. Wind speed peaked on October 5th at 6.17 m/s and on October 6th at 4.12 m/s. The ideal direction for the wind to come from, or the direction coming off the water towards the land, should be the north, east, or northeast; none of the significant winds from the campaign came from those directions.

Table 5

Start, end, and elapsed time for each sampling day at Lincoln Marina during the pilot study

Day	Start Time	End Time	Elapsed Time (hh:mm)
October 5 th	10:15	18:00	7:45
October 6 th	8:25	17:30	9:35

Table 6

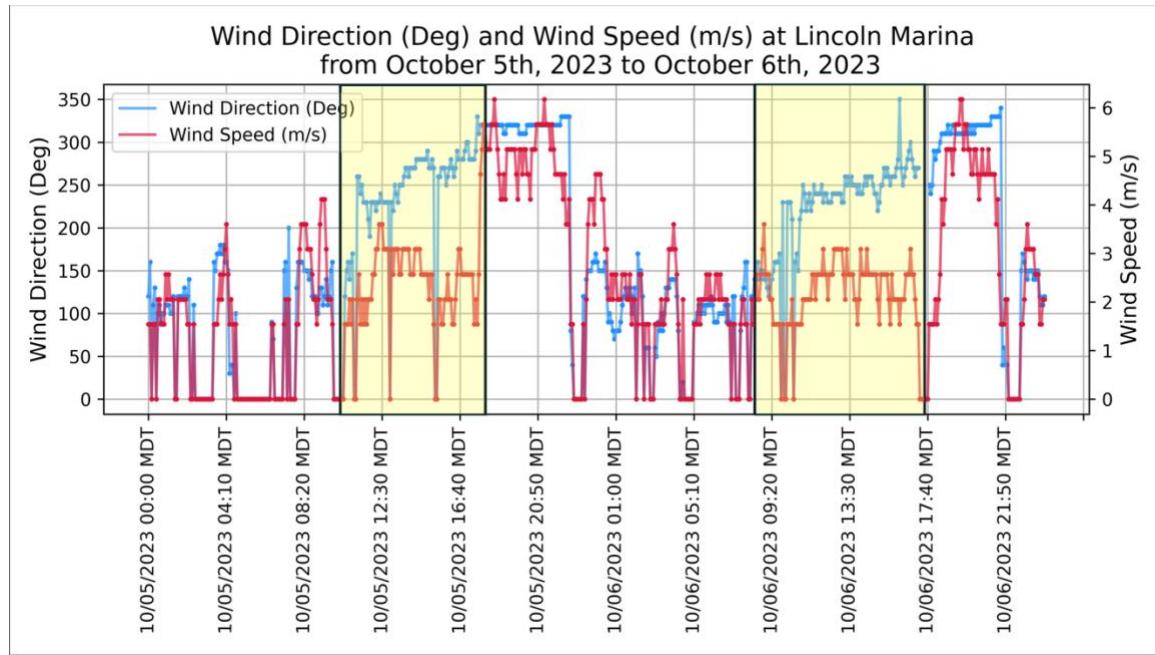
Daily statistics for temperature (°C) and relative humidity (%) at Lincoln Marina from October 5th, 2023, to October 6th, 2023

Statistic	Temperature (°C)	
	October 5 th	October 6 th
Average	15.0	16.1
Maximum	19.0	20.0
Minimum	8.00	9.00

Statistic	Relative Humidity (%)	
	October 5 th	October 6 th
Average	57.5	56.5
Maximum	87.2	81.5
Minimum	39.5	37.1

Figure 2

Time series showing wind direction (degrees) in blue and wind speed (m/s) in red at Lincoln Marina from October 5th, 2023, to October 6th, 2023

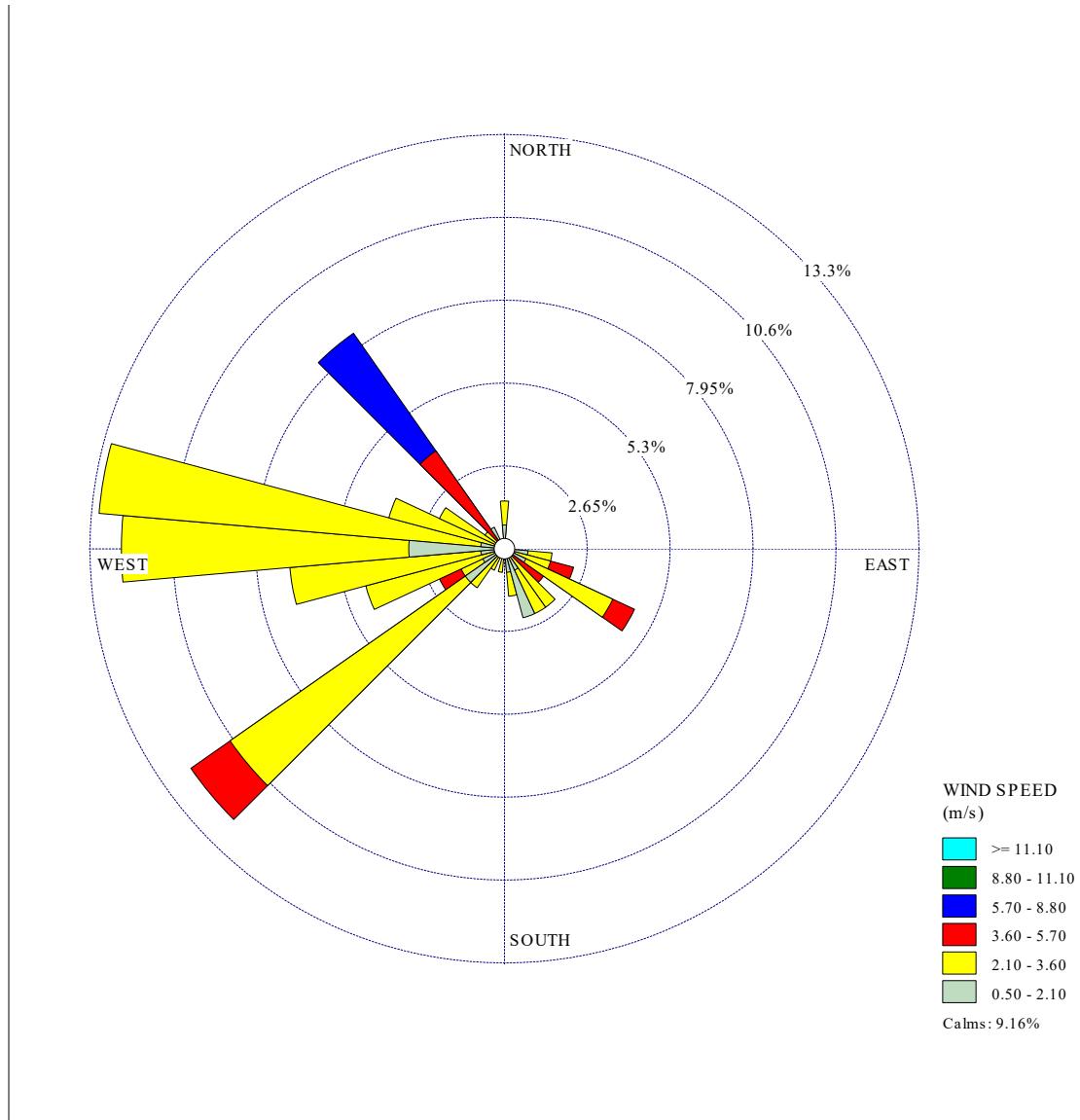


Note. The yellow shaded regions are the times the sampling occurred.

Figure 3

Wind rose diagram for Lincoln Marina during the preliminary studies sampling

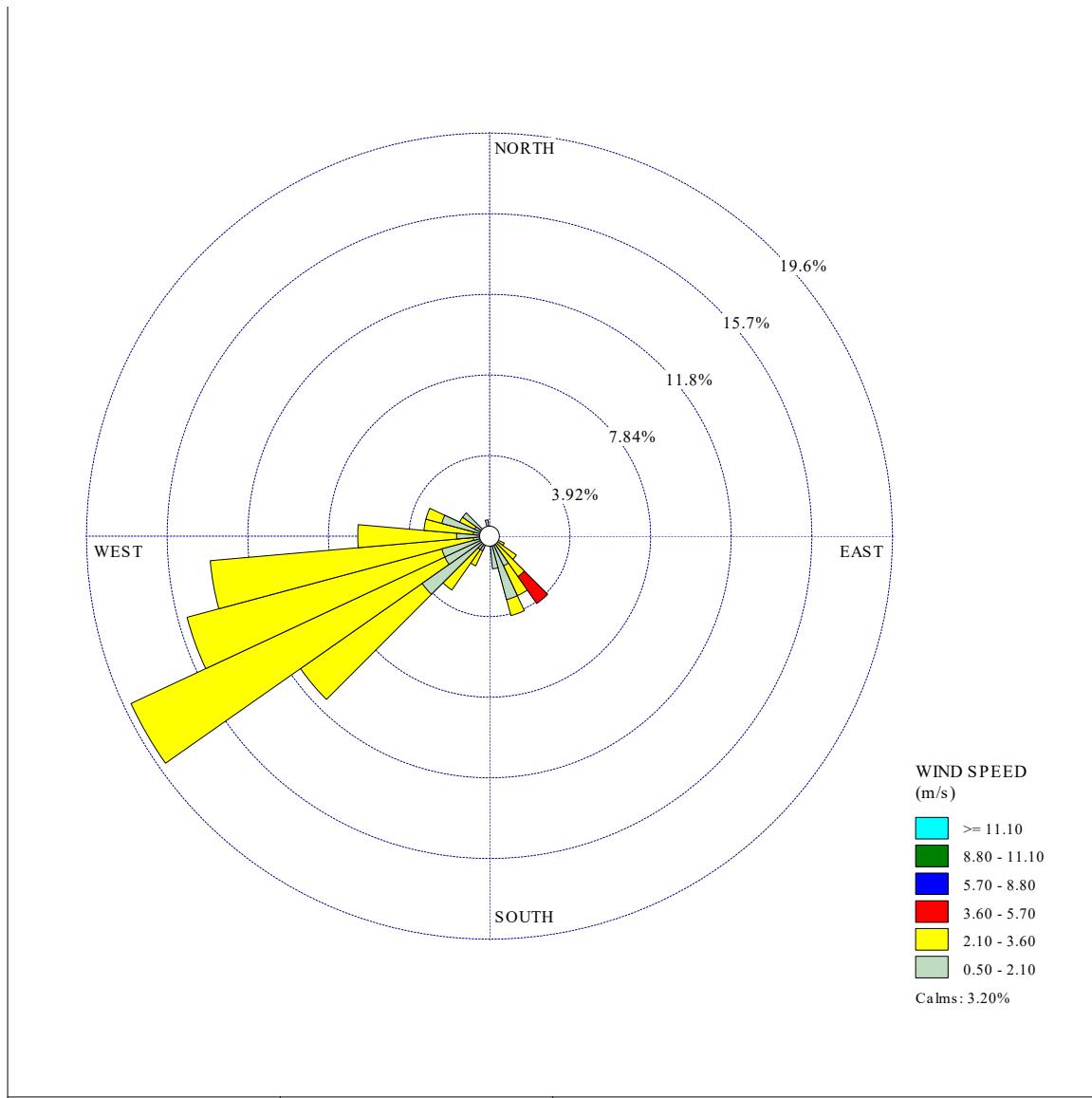
campaign for Thursday, October 5th, 2023



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 2.50 m/s with a calm wind percentage of 9.16%. Most wind came from the west/southwest, with the most intense wind coming from the northwest at 6.17 m/s.

Figure 4

Wind rose diagram for Lincoln Marina during the preliminary studies sampling campaign for Friday, October 5th, 2023



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed is 2.18 m/s with a calm wind percentage of 3.20%. Most wind came from the southwest, with the most intense wind being 4.12 m/s.

3.1.1.3. Sample Collection

3.1.1.3.1. Water Samples

Grab water samples were collected during the field campaign at the specified location (Figure 1). Grab samples were collected in triplicate at the same location three times a day. Samples were taken around 9 am, between 12 pm and 1 pm, and between 5 pm and 6 pm. The bottles were carefully dunked into the water to collect water samples without washing out any of the preservatives. Per EPA recommendations, each water sample collected was 100 mL in volume and was collected into a 150 mL amber screwcap bottle containing preservatives of 0.775 g of trizma, 0.2 g 2-chloroacetamide, and 0.035 g EDTA (Shoemaker et al., 2017). Once collected, the water samples were placed into a cooler in the field and then placed in a refrigerator in the lab. There were nine grab samples collected per day, leading to 18 total grab water samples.

In addition to the water samples, water quality data was recorded using a nke Instrumentation WiMo multiparameter sonde (nke Instrumentation, Hennebont, France) capable of recording timestamps, pressure (dbar), internal sonde temperature (°C), conductivity (mS/cm), water temperature (°C), dissolved oxygen concentration (mg/L), dissolved oxygen saturation percent, turbidity (NTU), and pH. The sonde records a different parameter every second in a rotating order, meaning that each parameter is collected once every five seconds; the order of collecting is dependent on the order the sensors were placed. The sonde was placed on the shore of Lincoln Marina at the location where water samples were collected and ran the entirety of the day (Figure 1). Data collection for October 5th began at 10:16 am and ended at 5:58 pm, while the data collection for October 6th began at 8:25 am and ended at 5:30 pm. The first and last 10

minutes of the sonde data were excluded from the analysis to allow the sonde time to adjust to the system and remove data corresponding to when the sonde was out of water.

3.1.1.3.2. Air Samples

Air samples were collected using two MiniVol TAS Portable Air Samplers (AirMetrics, Springfield, Oregon, United States) on 47 mm Teflon filters and one mid-vol Tisch PUF Pesticide Sampler (Tisch Environmental, Cleves, Ohio, United States) on a 4-inch (101.6 mm) quartz filter. Fisherbrand Acrylic and Bel-Art Dry-Keeper Desiccator Cabinets (Thermo Fisher Scientific, Logan, Utah, United States) were used to keep out moisture and maintain the humidity of the air filters before the trip. The MiniVol TAS Portable Air Samplers draw air in at a flow rate of approximately 5 L/min and run on a rechargeable lead-acid battery, while the Hi-Vol Tisch PUF Pesticide Sampler draws air in at a flow rate of 40 L/min and requires a generator or powerful battery to run; a gasoline generator and a full gas canister were brought along to power the Hi-Vol sampler. The air samplers were placed near the shore of Lincoln Marina (Figure 1) and ran between 8-12 hours per day. One filter was used per air sampler for a total of three air filter samples. All filters were stored in plastic Ziploc bags in coolers on ice between sampling days and when returning from the field campaign. The Teflon filters were stored in rubber-banded Petri dishes, and the quartz filters were placed in a foil envelope before being put in the Ziploc bag. The filters were placed in a 4 °C fridge after returning from the field. The filters were weighed before and after the field campaigns to determine how much mass had been collected onto each filter. Impactor heads for size fractionation were not used for these samples to collect and analyze all possible mass that went through the sampler, as it was not known at the time where the aerosols were going to lie in terms of

size. A log sheet was kept to record which filter went in which sampler, where each sampler was located, and how long each sampler ran each day.

3.1.1.4. Sample Analysis

3.1.1.4.1. Water Samples

The water samples were analyzed using the Solid Phase Extraction (SPE) and Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS) method as specified by the U.S. EPA (Shoemaker et al., 2017). This method consists of three different sections: sample preparation, SPE, and extract analysis. The sample preparation section is split into two procedures: Option A and Option B. The Option A procedure is for general samples, while the Option B procedure is for “highly concentrated” samples. While “highly concentrated” can be subjective, the general guideline is that if samples are semitransparent, use Option A, and if not, use Option B. For both options, 20 μ L of 50 ng/ μ L of ethylated MC-LR, d5(C2D5-MC-LR) (Cambridge Isotope) was added to all field samples and QC samples before filtration. While most of the samples qualified for Option A, four samples qualified for Option B (LM-S2-A, LM-S2-B, LM-S4-A, and LM-S4-B).

The Option A procedure started by vacuum filtering the 100 mL water sample through a 0.8 μ m polycarbonate Nucleopore filter into a 250 mL vacuum flask. An important note about the filtration is that the sample must be filtered within 8 hours, or the sample must be reanalyzed as Option B or flagged as suspect. After filtration was completed, the sample bottle was rinsed with 5 mL of 90/10 methanol/reagent water and filtered into the sample. The sides of the funnel were then rinsed with 2.5 mL of 90/10 methanol and filtered into the sample. Following the two rinses, the Nucleopore filter was removed with metal forceps and folded until it could fit in a 30 mL screwcap bottle,

where it was then filled with 2 mL of 80/20 methanol/reagent water, then placed in a -20 °C freezer for between 1 hour to 24 hours. After the time had passed, the bottles were removed from the freezer, and the 2 mL of liquid was transferred from the bottle to the vacuum flask with the sample. The filter was rinsed two more times, once with 2 mL 80/20 methanol/reagent water and once with 1 mL 80/20 methanol/reagent water, and both rinses were added to the sample. After both rinses, the sample was swirled to homogenize it, and it was ready for SPE.

The Option B procedure started with transferring 10 mL of the sample and 30 mL of methanol into a 50 mL centrifuge tube and placing the tube into a -20 °C freezer for between 2 hours and 24 hours. After the time had lapsed, the tubes were centrifuged at 8,000 rpm and 4 °C for 10 minutes. The centrifuged samples were then filtered through a 0.8 µm polycarbonate Nucleopore filter into a 250 mL vacuum. If the sample cannot be filtered within 8 hours, the sample is to be flagged as suspect. Once filtration had finished, the centrifuge tube was rinsed with 2 mL of 90/10 methanol/reagent water, passed through the filter, and added to the sample. Deionized water was then added to the sample until the total volume reached 150 mL, and the sample was then ready for SPE.

The first step for SPE was to turn the vacuum to a flow rate between 10 and 15 mL/min. SPE begins by attaching the cartridges to the extraction manifold and rinsing the cartridges with 15 mL of methanol in two 7.5 mL doses. After the methanol rinses, the cartridges were rinsed with 15 mL of reagent water in two 7.5 mL doses. After the reagent water rinse, 4-5 mL of the sample was added to the SPE cartridge, the sample transfer tube was attached to the top of the cartridge, and the remaining sample was added to the transfer tube and allowed to pass through the cartridge until all had passed. It

is critical to note that the SPE cartridges are not and cannot go dry unless explicitly stated. After the entire sample had passed through the cartridge, the sample bottles were rinsed with 10 mL of reagent water, which was then passed through the cartridge. The cartridge was then rinsed with 5 mL of reagent water, and air/nitrogen was sucked through the cartridge for 10 minutes to dry it. After 10 minutes, the air was turned off, the extraction manifold top was removed, and 15 mL Falcon tubes were placed into the extraction manifold underneath the spots where the cartridges reside. The extraction manifold top was replaced, and the sample bottles were rinsed with 5 mL of 90/10 methanol/reagent water and then added to the SPE cartridge.

The cartridges were soaked for 5-10 minutes before turning on the vacuum and allowing the methanol to pass. The sample bottle rinse was repeated once more and added to the cartridge to pass through for a total of 10 mL. After the SPE was completed, the Falcon tubes were transferred to a centrifuge tube and placed in a TurboVap II evaporator (Caliper Biotage, Uppsala, Sweden). The solvent was evaporated under a gentle stream of nitrogen in a heated water bath (60 °C) for approximately 1 hour or whenever the entire sample was evaporated. Following the evaporation, 980 µL of 90/10 methanol/reagent water was added to the centrifuge tubes, swished, and added to a 2 mL autosampler vial. In addition to the 90/10 methanol/reagent water, 20 µL of internal standards (cyclosporin-A 13C2, d4, Toronto Research Chemicals) were added to the 2 mL screwcap bottle for a total of 1 mL. The samples were ready for extract analysis using an Agilent 6940 Triple-Quad LC/MS with 1290 Infinity HPLC Front End (Agilent Technologies, Santa Clara, California, United States).

An Agilent Infinity 1290 liquid chromatograph (LC) interfaced with an Agilent 6490 triple quadrupole mass spectrometer/mass spectrometer (MS/MS) was used for quantifying the selected microcystin congeners plus nodularin in the water samples following EPA methodology (USEPA 2017), with specified quality control including field and trip blanks, laboratory reagent method blanks, laboratory fortified blanks, continuing calibration check samples, and use of an internal standard and extraction standard to evaluate instrument and method performance. Standard curves consisting of the eight analytes purchased from Enzo Biochem (Heptatotox set 1) were generated for each sample batch. The determined reporting limit accounting for sample concentration was 0.001 µg/L for all analytes except for MC-LR, with a reporting limit of 0.006 µg/L. Analytes were separated using ThermoScientific Synchronis C8, 2.1mm ID, 100 mm length, 1.7 µm particle size column at a flow rate of 9.4 ml/min. The mobile phase solution A was 20% mM ammonium formate, and solution B was 100% methanol. LC conditions and MS/MS parameters are given in Table A1 and Table A2. If the concentration in the sample was higher than the highest standard, the sample was diluted and rerun through the LC/MS/MS. Measured concentrations from the LC/MS/MS were divided by 100 to get the microcystin concentration in µg/L per 100 mL sample volume.

3.1.1.4.2. Air Samples

The air samples were analyzed using a modified version of the EPA's SPE and LC/MS/MS method described in section 3.1.1.4.1 (Shoemaker et al., 2017). Since the method for analysis of water samples for microcystins separates the sample using a filter with processing the filter by methanol extraction and freezing, the same approach was used for the air filter samples. To begin prepping the air samples for SPE, the small filters

were folded and placed into a 30 mL screwcap bottle with 15 mL of methanol, while the large filters were folded and placed into a 30 mL screwcap bottle with 20 mL of methanol; the air filters were not cut up like previous studies in the literature review since they could fit in the bottles when folded. Once the filters had been rinsed, the bottles were placed into a Kendal 12L 360W Commercial Grade Ultrasonic Cleaner and sonicated for 15 minutes at 32 °C. The sonicated samples were then placed into a -20 °C freezer for between 1.5 hours and 24 hours. After the freezer, the liquid samples were transferred into a 250 mL vacuum flask while the filters remained in the bottles. The 30 mL bottle with the filter was then rinsed with 4 mL of 80/20 methanol/reagent water, and then 4 mL of 80/20 methanol/reagent water was added to the vacuum flask. This rinsing process was repeated two more times, this time using 2 mL of 80/20 methanol/reagent water per rinse. After the third rinsing, deionized water is added to the flask to reach 250 mL, where the samples are now ready for SPE. Before SPE, 50 µL of the external standards were added directly to the vacuum flask since there was no filtration step, and the sample was swirled to homogenize it. The remaining steps through SPE and extract analysis were unchanged.

3.1.1.5. Quality Assurance and Quality Control

To ensure that the collected samples and subsequent analytical results were accurate, precise, and free from contamination, a series of quality control measures was implemented both during field collection and laboratory analysis. Water samples were collected in triplicate to assess sampling precision; air samples could not be collected in triplicate due to equipment limitations. The preservatives used in the water samples expire after 28 days; thus, all samples were analyzed within this period. A standardized protocol for glassware cleaning was established to prevent contamination of sampling

bottles before field deployment and to avoid cyanotoxin contamination during laboratory preparation and analysis. Pre-weighed air filters were stored in Fisherbrand Acrylic or Bel-Art Dry-Keeper desiccator cabinets (Thermo Fisher Scientific, Logan, Utah, United States) to maintain humidity control before use. Equipment blanks and trip blanks were incorporated to identify potential sources of contamination: a positive equipment blank indicated contamination originating from the sampling apparatus, while a positive trip blank indicated bottle contamination. Samples were preserved on ice immediately following collection; two coolers were used during field campaigns—one for daily collection and another stationed at the hotel to minimize repeated transport. Upon return to the laboratory, samples were transferred to refrigerated storage. Each sample bottle was individually labeled, and sets of triplicate samples were stored in labeled Ziploc bags to maintain sample integrity and prevent label damage caused by melting ice.

For laboratory analysis, all water samples were spiked with internal isotopically labeled standards to monitor and correct for instrument drift, as well as an isotopically labeled extraction standard to correct for extraction efficiencies. The LC/MS/MS system used for cyanotoxin quantification was calibrated using multiple standards to ensure accuracy. A laboratory control sample (LCS) was included in each batch to verify method accuracy using a known concentration, and a continuing calibration verification (CCV) check was performed after every ten samples to monitor and prevent instrument drift. Reporting limits for the targeted cyanotoxins were established based on instrument sensitivity: for most microcystin congeners, the reporting limit was 0.1 µg/L, whereas MC-YR had a reporting limit of 0.2 µg/L. Due to the concentration step during sample preparation (1 mL from 100 mL), the effective reporting limits for water samples were

reported as 0.001 µg/L and 0.002 µg/L, respectively. The reporting limits were determined based on the precision and accuracy of the LC/MS/MS (Shoemaker et al., 2017). Comprehensive field notes were maintained throughout sample collection and analysis.

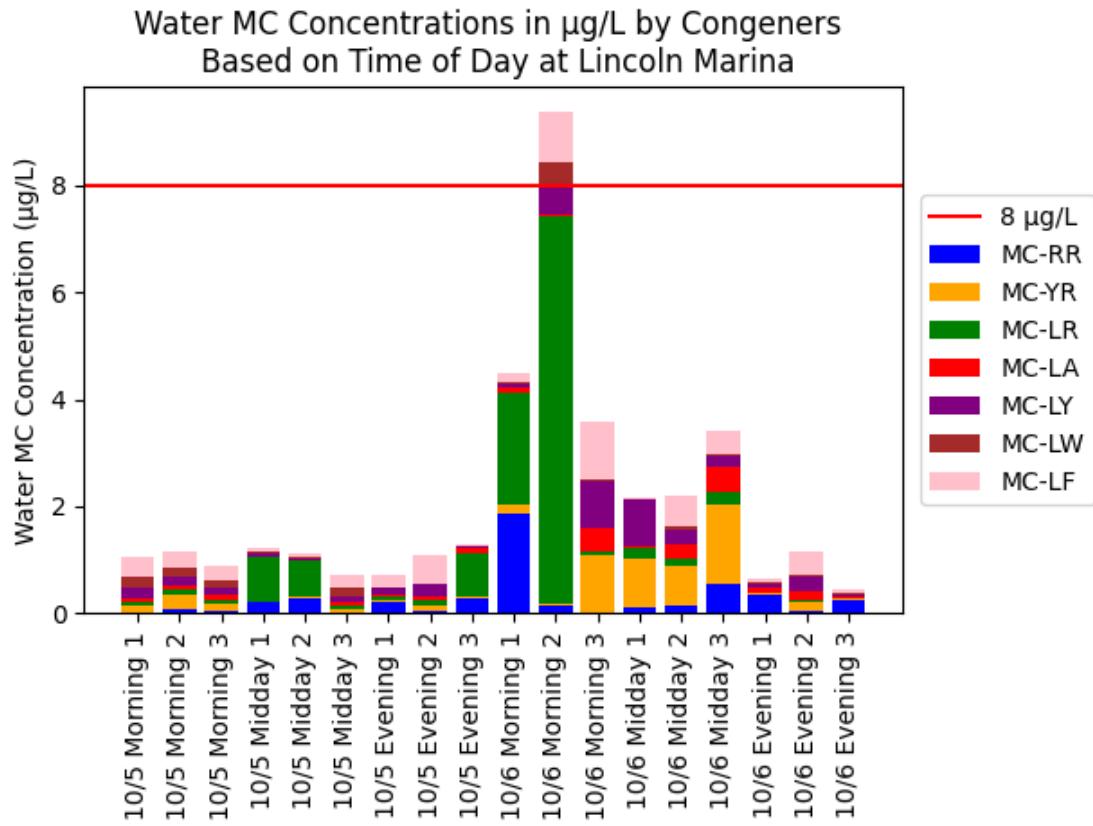
3.1.2. Results

3.1.2.1. Water Samples

All water samples had detectable concentrations for every microcystin congener (Figure 5). MC-LR was the dominant congener and the primary driver for the total microcystin concentration, while MC-LA and MC-LW were the least common congeners. The October 6th morning samples had the highest total microcystin concentrations, with replicate 2 being the highest at 9.37 µg/L; Replicate 2 was also the only sample that had a total microcystin concentration higher than the UDEQ's warning threshold of 8 µg/L (Utah Department of Environmental Quality, 2025b); there is no clear or explicit reason as to why this is. The October 5th sample concentrations were constant over the day from morning to evening, while the October 6th samples were the highest during the morning and decreased as the day went on (Figure 6). Single Factor ANOVA analysis ($\alpha = 0.05$) using log transformed values showed that time of collection was not a significant factor ($P\text{-value} = 0.060$), while day of collection was ($P\text{-value} = 0.038$). Raw values can be seen in Table B1.

Figure 5

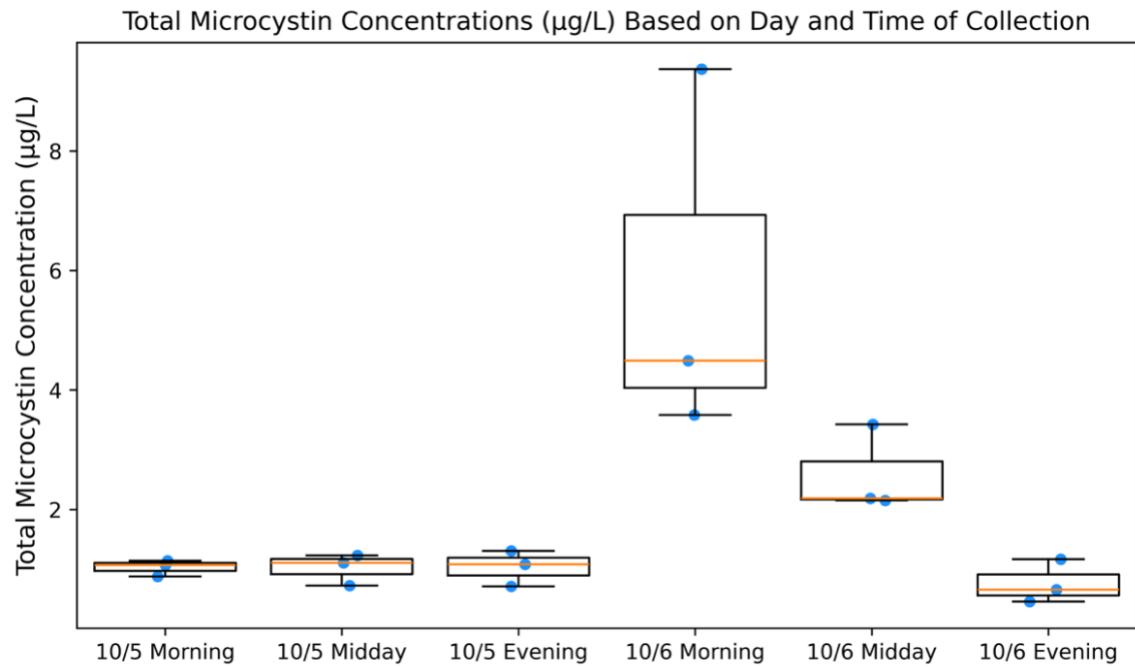
Total MC concentrations and MC congener concentrations for water samples for the Lincoln Marina preliminary study from October 5th to October 6th, 2023



Note. Only one sample (10/6 Morning 2) had a total MC concentration higher than the UDEQ's warning threshold of 8 µg/L.

Figure 6

Boxplots with scatter points showing the distribution of the water samples by sample collection time in µg/L for the Lincoln Marina preliminary study from October 5th to October 6th, 2023



3.1.2.2. Air Samples

To determine the microcystin concentrations on the air filters, the three blanks for the mid-volume and low-volume filters were averaged together and then subtracted from the measured concentration of the field filters. If the concentrations were above the reporting limit (<0.2 µg/L for MC-YR and <0.1 µg/L for all other MC congeners), the concentrations in µg/L were converted to mass/m³ using the mass collected on the filter. Raw values can be seen in Table B2. The only detectable microcystin concentrations on the filters were for MC-LR. However, the blank filters had higher readings for MC-LR

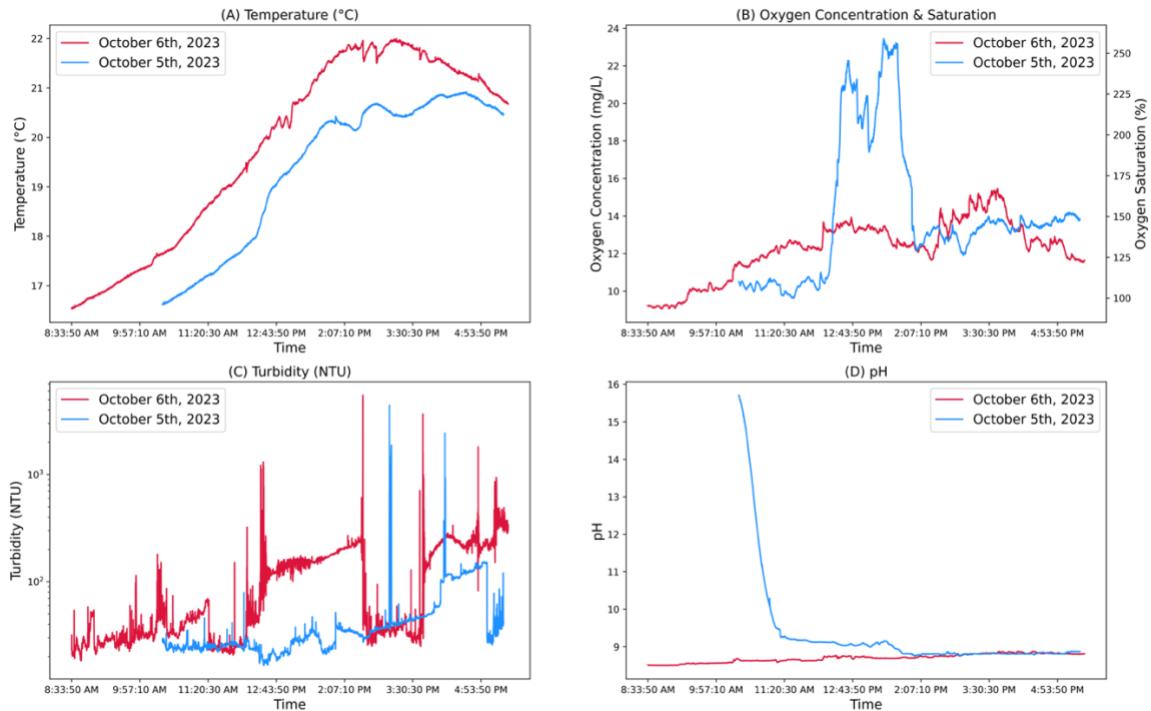
than the field filters; therefore, there were no detectable microcystin concentrations on any of the air filters.

3.1.2.3. Water Quality Parameters

Temperature increases as the day goes on until it reaches its peak around 3:30 pm or 4 pm and then decreases (Figure 7A) Dissolved oxygen concentration and saturation increase as the day goes on and then decrease as the sun sets (Figure 7B). There are some differences between the two days, as the October 5th data spikes earlier, around noon, and reaches a higher peak of around 24 mg/L (~250% saturation) but then returns to normal (12 mg/L) around 2 pm and stays consistent. The October 6th data rises steadily until 3:30 pm, where it reaches a peak of 15-16 mg/L, where it declines afterward. These saturation percentages are extremely high, but the UDEQ has found and reported values of 200% plus at Utah Lake in the past. Figure 7C-D shows that there is no strong correlation between turbidity and time or pH and time. The October 5th, 2023, pH data is questionable, as the pH reads as unobtainable at a value above 12 for at least one hour before it stabilizes around 9, which matches well with the October 6th, 2023, data and the historical values from the UDEQ of 9.3.

Figure 7

(A) Time series showing temperature change over the day. (B) Time series showing oxygen concentration in mg/L and oxygen saturation in percentage over the day. (C) Time series showing turbidity in NTUs over the day. (D) Time series showing pH over the day



Note. Blue represents October 5th, 2023, while red represents October 6th, 2023.

3.1.3. Discussion

3.1.3.1. Water Samples

Microcystins were found in the water at Lincoln Marina. One of the samples, 10/6 Morning 2, had a total microcystin concentration above the warning advisory of eight µg/L (Utah Department of Environmental Quality, 2025a). This lines up well with the fact that a warning advisory was issued by the UDWR and UCHD the week before and after

the sampling campaign, but not during the week we sampled (Utah Division of Water Quality, 2023). It is unknown if this is because the UDWR didn't take any measurements during this period or if they did sample but did not record any results over the threshold. ANOVA analysis showed that time of collection was not a significant factor, while the day of collection was. There is no clear or explicit reason as to why the concentrations on October 5th and 6th were so different; it is entirely possible that a bloom was sampled into on October 6th but not on October 5th.

3.1.3.2. Air Samples

While there were some concentrations of MC-LR found on the field filters, the concentration of MC-LR on the blanks was greater. Given the current methodology to subtract the blank concentrations from the field concentrations, this gave a result of no detectable microcystin concentrations on any of the filters. Further testing was determined to be required to assess whether subtracting blank filters with detectable concentrations from the field samples is the correct methodology for analyzing microcystin air filters. Given that microcystins were found on both the blanks and field samples, there is some foundation that the methodology for determining microcystins on air filters is viable. However, given that the microcystin concentrations in the air are unknown, it is impossible to determine just from this study if the readings were due to a methodology error, contamination, or if there were no microcystins present in the air. Further testing was required, which included repeating the analysis with filters spiked with known concentrations of microcystins, which is described in section 3.2.

3.1.3.3. Water Quality Parameters

The water temperature increases and decreases roughly in line with the hours of sunlight; it increases as the sun rises and decreases as the sun sets. The dissolved oxygen saturation follows a biologically driven system, where dissolved oxygen increases dramatically during the sunlight hours; this corresponds to a system with a lot of plant life/algae. Looking at the water temperature and dissolved oxygen concentrations suggests that most algae activity occurs between 1 pm and 3 pm, meaning it would be ideal to take water samples around that time. While pH is an important parameter for HABs, the range of values for each day is small, with 0.530 for October 5th and 0.615 for October 6th. It might be beneficial to swap out the turbidity and pH meters on the sonde for sensors that can read chlorophyll-a or phycocyanin, which can provide information about plant life (algae) in the water. The pH reading for October 5th is concerning, as it should not be possible to have a pH above 12, and the sonde reads above 12 for at least 1 hour; this is assumed to be an instrument reading error. The error is most likely due to the sonde or the pH meter not adjusting to the water, so it might be beneficial to prime the sonde/meter in a bucket of representative water before deploying it into the water body of interest.

3.2 Air Filter Spike Recovery Analysis

Following the preliminary studies campaign at Lincoln Marina in October 2024, a filter spike recovery analysis QA/QC check was performed to determine whether the devised methodology could adequately analyze air filters for microcystins.

3.2.1. Methods

To test if this methodology for analyzing microcystins on air filters was viable, the previously described methodology for analyzing air samples described in section 3.1.1.4.2 was repeated using blanks and spiked filters. Twelve total samples were analyzed: three methanol blanks (no filters), three filter blanks, three filters spiked with 100 µL of 20 µg/L microcystin, and three filters with 100 µL spiked with 100 µg/L microcystin. After LC/MS/MS analysis, the percent recovery for every congener in the samples was calculated by determining how much the concentration of the congener was relative to the known concentration. Every filter used for this experiment was a 47 mm Teflon filter.

3.2.2. Results

Table 7 shows the percent recoveries for the microcystin congeners concentrations for each replicate of the spiked air filters, and Table 8 shows the averages and standard deviations for surrogate percent recoveries for the microcystin congeners concentrations for the spiked air filters. One 20 µg/L spike, 8831, was excluded from analysis since it was not spiked with the correct amount of microcystin. One 100 µg/L spike, 8835, had results significantly different from the other two 100 µg/L spikes but could not be excluded. Most congeners performed relatively well and were similar to each other regarding percent recovery, except for MC-LR and MC-LW. MC-LR was the biggest overperformer of the congeners, as it was the only congener to regularly have percent recoveries greater than 100% for both the 20 µg/L and 100 µg/L spikes. MC-LW was the biggest underperformer of the congeners, as two of the five samples had zero percent recovery, and the three samples that did have percent recoveries were in the single digits.

As groups, the 20 µg/L spikes tended to underperform relative to their 100 µg/L spike counterparts, except for MC-LR, where the 20 µg/L spikes overreported the percent recovery at a group average of 149% versus 96.8% for the 100 µg/L spikes. The percent recovery differences between the 20 µg/L spikes and the 100 µg/L spikes were not massive but noticeable. The 100 µg/L spikes overall reported good percent recoveries except for filter 8835, which was between 30% to 50% of the percent recoveries of the other 100 µg/L spikes. For both the methanol and filter blanks, all congener concentrations except MC-LR and MC-LA were under the detection limit. All six blanks had MC-LR concentrations, with the average methanol blank concentration at 1.04 µg/L ± 0.320 µg/L and the average filter blank concentration at 0.984 µg/L ± 0.131 µg/L. The average MC-LR concentration in the 20 µg/L spikes was 2.98 µg/L ± 0.530 µg/L and the average MC-LR concentration in the 100 µg/L spikes was 9.68 µg/L ± 1.71 µg/L. Only one filter blank had a detectable concentration of MC-LA at 0.105 µg/L.

Table 7

Percent recoveries for the nodularin and microcystin congeners for the spiked air filters.

Name	Nodularin	MC-YR	MC-RR	MC-LR	MC-LA	MC-LY	MC-LW	MC-LF
8810 - 20 μg/L	64.8	57.3	65.3	122	84.6	57.3	0.00	69.2
8832 - 20 μg/L	85.9	54.9	70.6	175	75.8	84.0	7.91	89.7
8833 - 100 μg/L	97.4	97.4	102	109	101	99.1	1.01	94.8
8834 - 100 μg/L	99.0	99.2	93.9	109	105	103	0.00	87.2
8835 - 100 μg/L	54.8	56.1	63.6	72.7	58.7	54.0	1.28	65.1

Note. Filters were spiked with 100 μL of 20 and 100 μg/L standards.

Table 8

Averages and standard deviations for the percent recoveries for the nodularin and microcystin congeners for the spiked air filters

Average	Nodularin	MC-YR	MC-RR	MC-LR	MC-LA	MC-LY	MC-LW	MC-LR
20 μg/L	75.3	56.1	67.9	149	80.2	70.6	3.98	79.5
100 μg/L	83.7	84.2	86.5	96.9	88.1	85.3	0.76	82.4
Standard Deviation	Nodularin	MC-YR	MC-RR	MC-LR	MC-LA	MC-LY	MC-LW	MC-LR
20 μg/L	10.5	1.23	2.65	26.5	4.40	13.3	3.96	10.2
100 μg/L	20.5	19.9	16.6	17.1	20.9	22.2	0.55	12.6

Note. Filters were spiked with 100 μL of 20 and 100 μg/L standards.

3.2.3. Discussion

The results showed that this methodology could extract liquid microcystins from 47 mm Teflon filters, with the major caveat that the methodology performed better when the concentration on the filter was higher. This could pose some issues, as the concentrations in the air at Utah Lake are more than likely to be on the lower end of the concentrations. The difference between the 20 µg/L spikes and the 100 µg/L spikes was not massive but was noticeable. The poor performance of MC-LW is particularly unknown, but it can either be explained by a low concentration of MC-LW in each of the spikes or bad chromatography by the LC/MS/MS. The overperformance of MC-LR is also unknown but can be explained by the LC/MS/MS mistakenly identifying another compound as MC-LR. There is a possibility that either the filters or methanol has some detectable amount of MC-LR contamination, but the blank concentration results showed that the MC-LR concentrations in the blanks were much lower when compared to the filter spikes. Furthermore, given the conditions and lab protocols of both the air quality and chemistry lab, there is no reasonable explanation for the methanol or filters being contaminated. Future research will need to be done to determine the causes of the performance of MC-LR and MC-LW, and whether this method can truly work with air particles.

3.3 Conclusions

Between the pilot air sampling study and the air filter spike analysis, these preliminary studies showed what worked for the methodology and what needed to be changed. While there was initial concern that the air sample collection and analysis methodology did not work in the pilot study, the air sample analysis methodology was

proven successful through the filter spikes. This suggests that modifications should be made to the air sample collection methodology to collect more mass, such as increasing the time of collection from two days to at least four days. Neither the low-volume nor mid-volume air samplers were able to produce detectable amounts of microcystins in the pilot air sampling study. Given that neither sampler type showed to be superior to the other, low-volume air samplers were chosen since more low-volume air samplers could be deployed throughout the site. More air samplers would allow for the collection of microcystin aerosol samples and would allow for samples to be collected throughout the entire site rather than a single location. The pH and turbidity sensors for the sonde did not provide super useful information, as the pH did not change much throughout the day, and the turbidity ultimately did not reveal much. It would be very beneficial to change out the pH and turbidity sensors for chlorophyll-a and phycocyanin sensors to get a baseline for the amount of plant life in the waters and use a single pH measurement to determine pH. Changing the water sampling schedule from three times a day at one location to one time day (around noon) at multiple locations would allow for a better understanding of microcystin concentrations in the water across the entire sampling site.

CHAPTER 4

METHODS

4.1 Site/Sample Location and Timeline

4.1.1. Lincoln Beach

The Lincoln Beach campaign was conducted at Lincoln Beach Marina in Spanish Fork, Utah, from Monday, July 8th, 2024, to Thursday, July 11th, 2024. Sample locations for air and water grab samples are denoted in Figure 8 and composite water samples collected by USV locations are shown in Figure 9. The Utah Division of Water Resources (UDWR) and Utah County Health Department (UCHD) issued a warning advisory for Utah Lake the week of July 8th, 2024, indicating that a cHAB was present at Utah Lake. Lincoln Marina was chosen due to it being a historical hot spot of cHAB activity at Utah Lake with heavy recreation traffic (Randall et al., 2019; Tate, 2019).

Figure 8

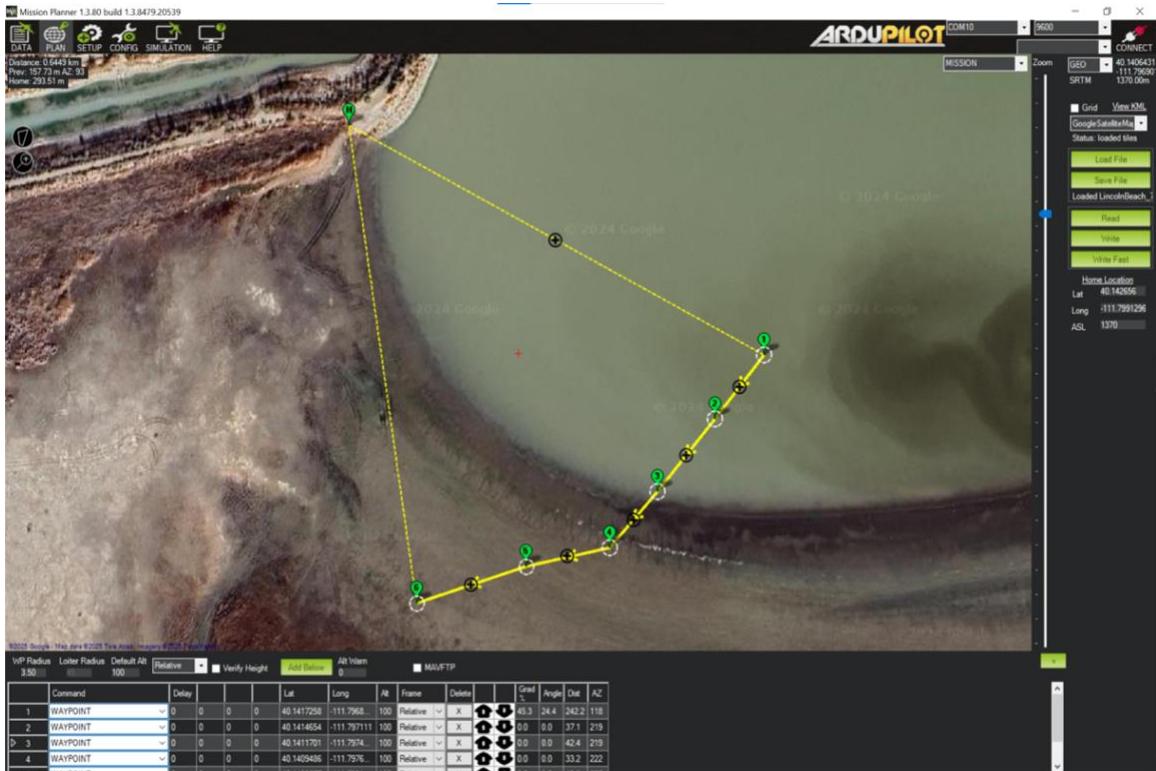
Sampling Layout of the Lincoln Marina campaign



Note. Air sample sites are in red, labeled with Sampler ID, while the water samples are in green (Google Earth, 2025).

Figure 9

Launch point (H) and six sample sites along a transect toward the shore used to collect the composite samples at Lincoln Marina using the USV



Meteorology data for this sampling campaign were collected from the MesoWest station KPVU, Provo Municipal Airport, from Monday, July 8th, 2024, to Thursday, July 11th, 2024. The start, end, and elapsed times for each sampling day can be seen in Table 9; only meteorological data during the sampling period were used. The 4-day average station pressure was 650 mmHg, the average temperature was 31.1 °C, and the average relative humidity was 21.6%; daily temperature and relative humidity data can be seen in Table 10. A timeseries of wind data can be seen in Figure 10 and a wind rose for July 8th to July 11th can be seen in Figure 11, Figure 12, Figure 13, and Figure 14, respectively. For July 8th, the average wind speed was 2.63 m/s from the west, 2.74 m/s from the

southwest on July 9th, 2.54 m/s from the west on July 10th, and 3.37 m/s from the west or northwest on July 11th. Wind speed peaked on July 8th at 4.12 m/s, 4.12 m/s on July 9th, 4.63 m/s on July 10th, and 7.72 m/s on July 11th. The ideal direction for the wind to come from, or the direction coming from the lake towards the land, would be the north, east, or northeast. While there was some wind coming from the southeast on July 9th and July 11th, most wind did not come from those directions.

Table 9

Start, end, and elapsed time for each sampling day at Lincoln Marina during the summer 2024 campaign

Day	Start Time	End Time	Elapsed Time (hh:mm)
July 8 th	9:20	19:35	10:15
July 9 th	9:15	19:25	10:10
July 10 th	8:55	19:10	10:15
July 11 th	8:30	17:55	9:25

Table 10

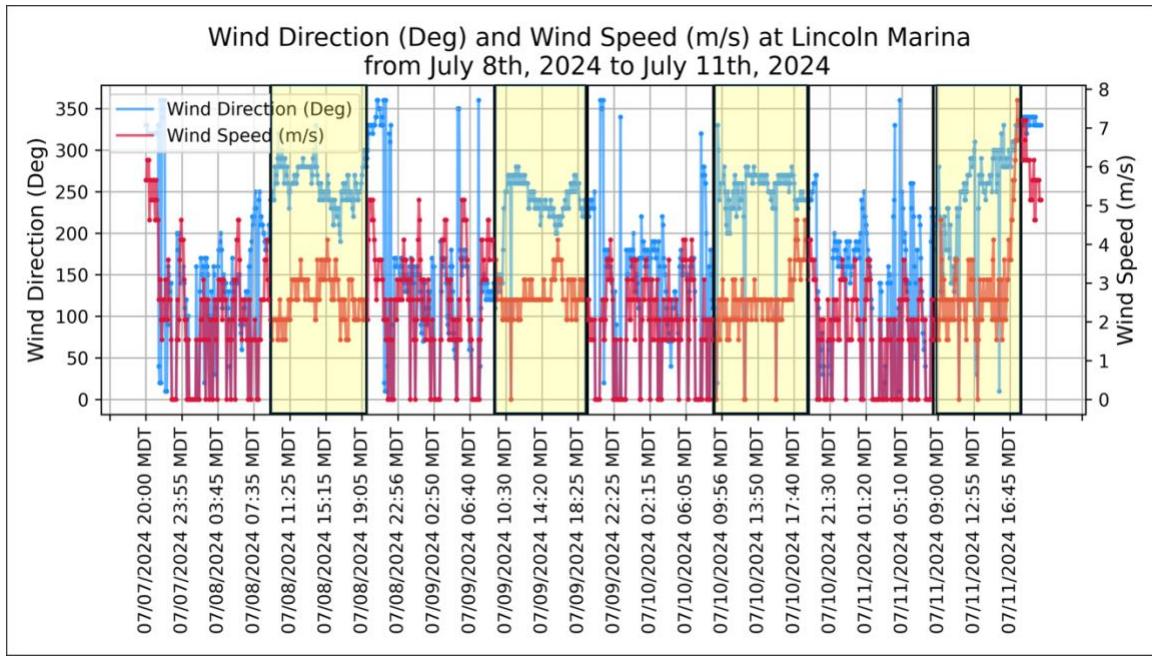
Daily statistics for temperature (°C) and relative humidity (%) at Lincoln Marina from July 8th, 2024, to July 11th, 2024

Statistic	Temperature (°C)			
	July 8 th	July 9 th	July 10 th	July 11 th
Average	28.3	30.1	32.1	33.9
Maximum	32.0	22.0	37.2	39.4
Minimum	22.0	34.4	23.0	26.0

Statistic	Relative Humidity (%)			
	July 8 th	July 9 th	July 10 th	July 11 th
Average	23.1	21.1	21.8	20.4
Maximum	40.6	35.4	37.3	35.1
Minimum	10.9	12.2	8.44	7.57

Figure 10

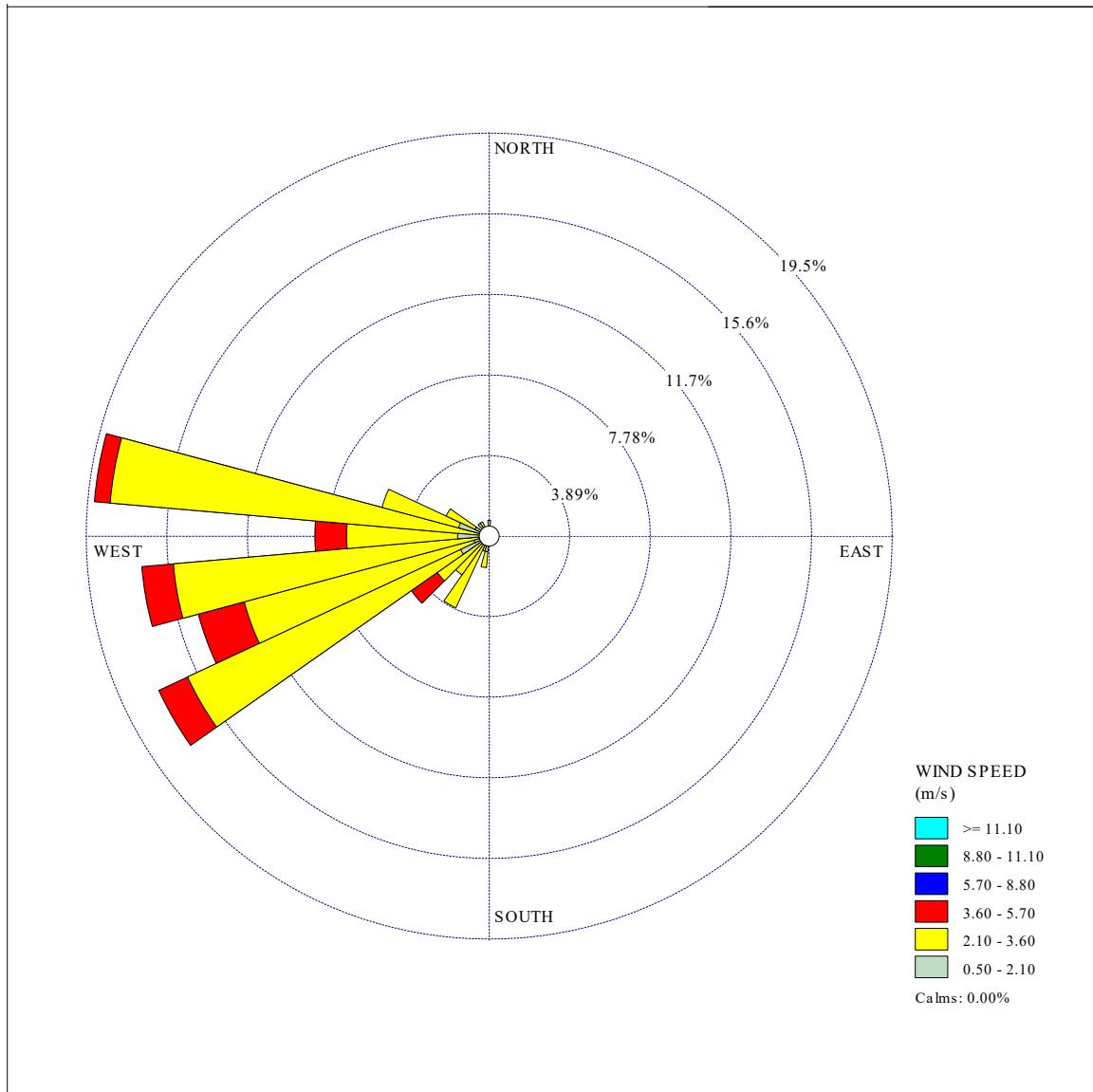
Time series showing wind direction (degrees) in blue and wind speed (m/s) in red at Lincoln Marina from July 8th, 2024, to July 11th, 2024



Note. The yellow shaded regions are the times the air sampling occurred.

Figure 11

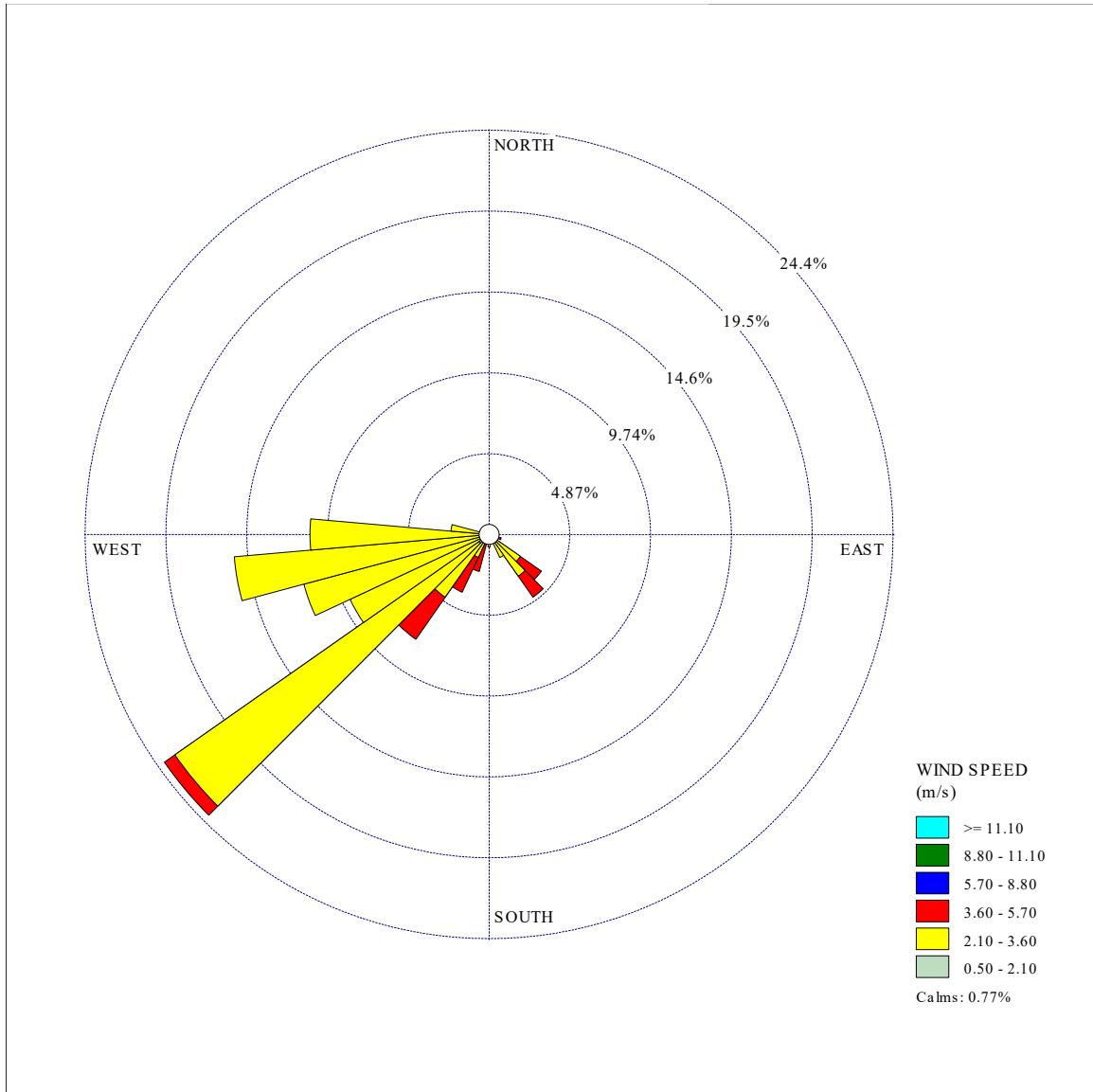
Wind rose diagram for Lincoln Marina for Monday, July 8th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 2.63 m/s with a calm wind percentage of 0.00%. Most of the wind is coming from the west, with the most intense wind at 4.12 m/s.

Figure 12

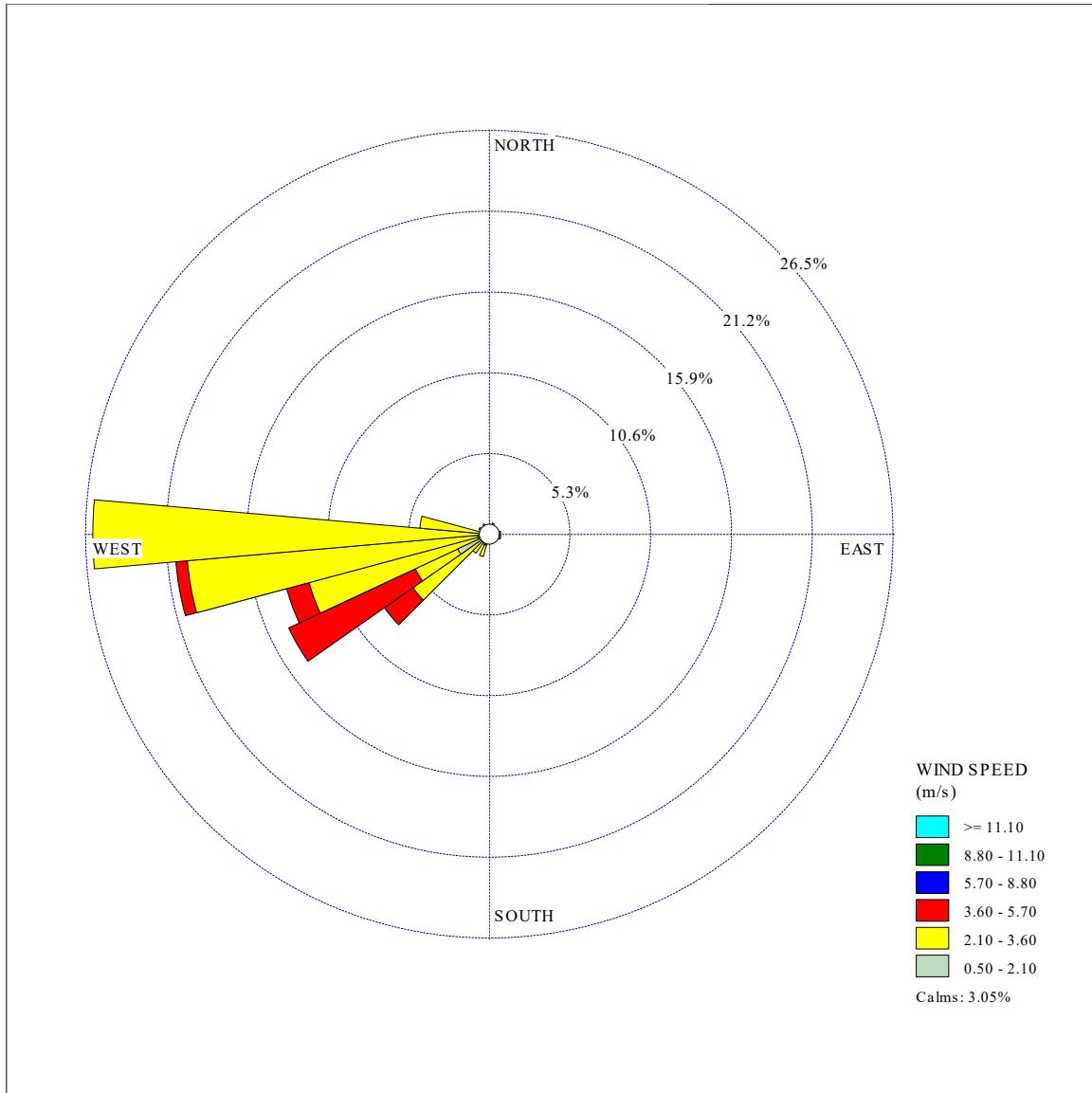
Wind rose diagram for Lincoln Marina for Tuesday, July 9th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 2.74 m/s with a calm wind percentage of 0.77%. Most of the wind is coming from the southwest, with some more intense winds coming from the southeast at 4.12 m/s.

Figure 13

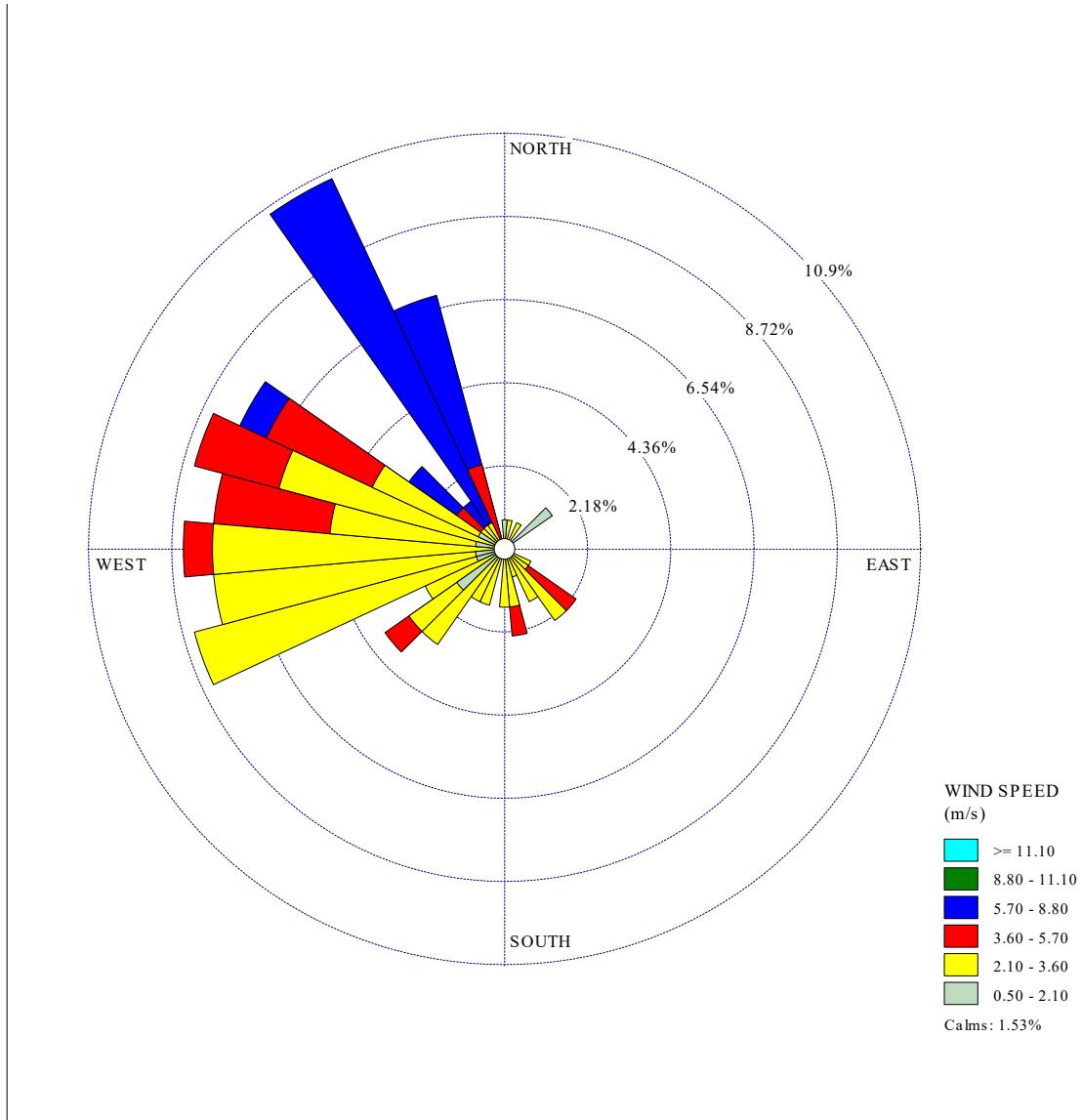
Wind rose diagram for Lincoln Marina for Wednesday, July 10th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 2.54 m/s with a calm wind percentage of 3.05%. Most of the wind is coming from the west, with some more intense winds coming from the southwest at 4.63 m/s.

Figure 14

Wind rose diagram for Lincoln Marina for Thursday, July 11th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 3.37 m/s with a calm wind percentage of 1.53%. Most of the wind is coming from the west or northwest, with some more intense winds coming from the northwest at 7.72 m/s.

4.1.2. Utah Lake State Park

The Utah Lake State Park campaign was conducted at Utah Lake State Park in Provo, Utah, from Monday, August 12th, to Thursday, August 15th, 2024. All air and water grab sample locations are denoted in Figure 15 and composite water sample locations collected by USV are shown in Figure 16. The UDWR and UCHD issued a warning advisory for Utah Lake the week of August 12th, 2024, indicating that a cHAB was present at Utah Lake (Utah Division of Water Quality, 2024). Utah Lake State Park was chosen due to it being near historical hot spots of cHAB activity at Utah Lake with very heavy recreational traffic (Randall et al., 2019; Tate, 2019). Utah Lake State Park was chosen as the second campaign site over a return trip to Lincoln Marina to help get a better baseline of microcystin aerosol at various locations at Utah Lake.

Figure 15

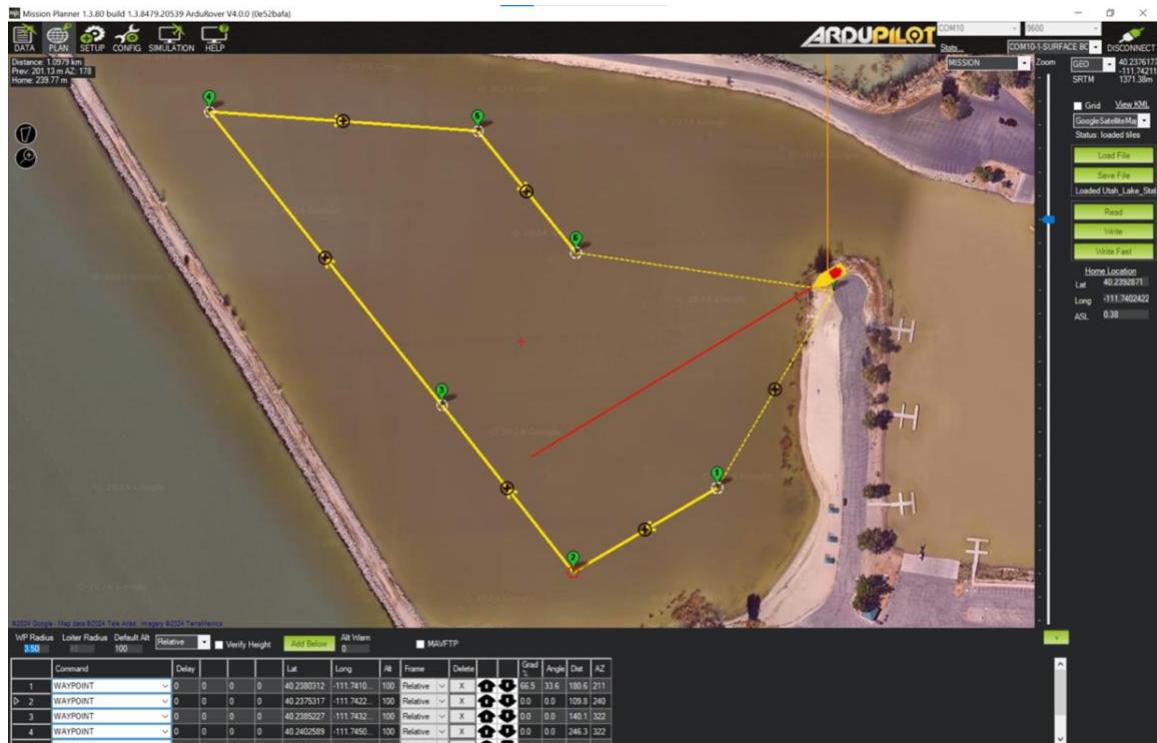
Sampling Layout of the Utah Lake State Park campaign



Note. Air sample sites are in red, labeled with Sampler ID, while the water samples are in green (Google Earth, 2025).

Figure 16

Launch point (H) and six sample sites within the marina used to collect the composite samples at Utah Lake State Park using a USV



Meteorology data for this sampling campaign were collected from the MesoWest station KPVU, Provo Municipal Airport, from Monday, August 12th, 2024, to Thursday, August 15th, 2024. The start, end, and elapsed times for each sampling day can be seen in Table 11; only meteorological data during the sampling period were used. The 4-day average station pressure was 653 mmHg, the average temperature was 26.6 °C, and the average relative humidity was 41.7; daily temperature and relative humidity data can be seen in Table 12. A timeseries of wind data can be seen in Figure 17, and a wind rose for August 12th to August 15th can be seen in Figure 18, Figure 19, Figure 20, and Figure 21, respectively. For August 12th, the average wind speed was 6.30 m/s from the southeast, 4.30 m/s from the southeast on August 13th, 2.79 m/s from multiple directions on August

14th, and 2.79 m/s from the south on August 15th. Wind speed peaked on August 12th at 13.4 m/s from the southwest and northwest, 12.9 m/s from the southeast on August 13th, 10.3 m/s from the southwest on August 14th, and 6.69 m/s from the south on August 15th. It should be noted that the wind speeds on August 12th, in combination with severe weather/rain, forced sampling to end earlier than anticipated. The ideal direction for the wind to come from, or the direction coming from the lake towards the shore, would be the west, northwest, or southwest. While there was significant wind from those directions on all days except August 13th, most wind came from the southeast; August 12th was notable as the most extreme wind of the campaign came from the northwest on that day.

Table 11

Start, end, and elapsed time for each sampling day at Utah Lake State Park during the summer 2024 campaign.

Day	Start Time	End Time	Elapsed Time (hh:mm)
August 12 th	9:15	17:15	8:00 ^a
August 13 th	8:40	18:30	9:50
August 14 th	8:35	18:35	10:00
August 15 th	8:20	18:15	9:55

^aAugust 12th's sampling was cut short due to severe weather, extreme winds, and rain.

Table 12

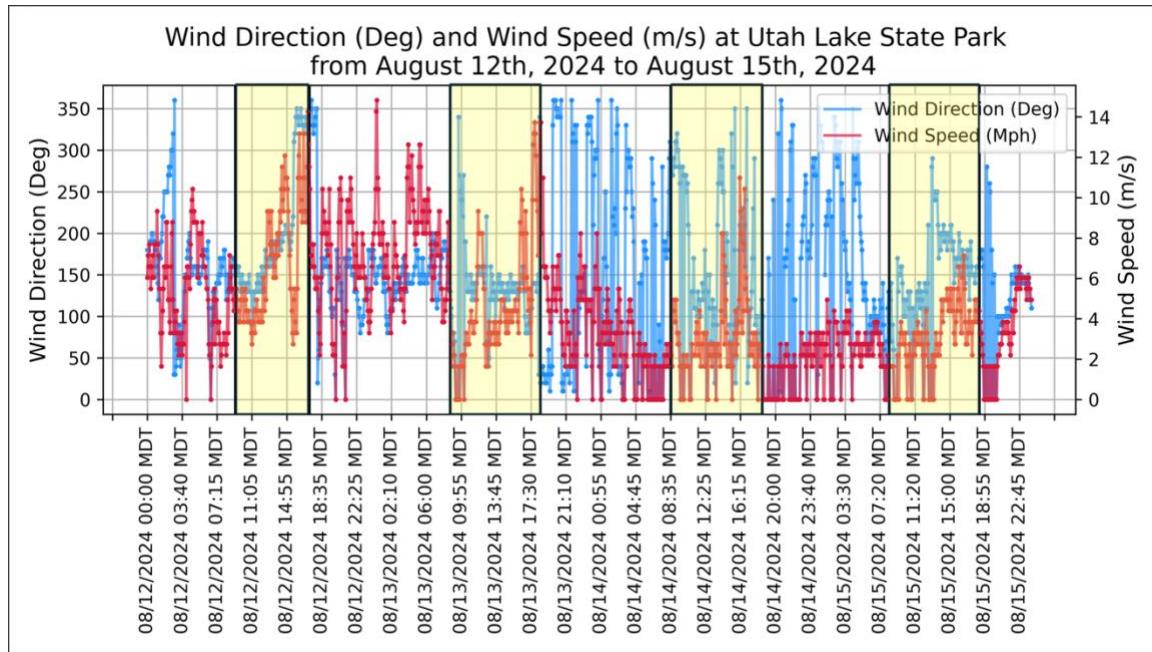
Daily statistics for temperature (°C) and relative humidity at Utah Lake State Park from August 12th, 2024, to August 15th, 2024

Statistic	Temperature (°C)			
	August 12 th	August 13 th	August 14 th	August 15 th
Average	25.8	24.9	25.9	29.9
Maximum	32.0	29.4	27.0	33.0
Minimum	19.0	18.9	21.0	21.0

Statistic	Relative Humidity (%)			
	August 12 th	August 13 th	August 14 th	August 15 th
Average	52.0	51.2	37.3	25.0
Maximum	82.9	77.6	60.3	52.8
Minimum	33.7	35.1	21.6	14.1

Figure 17

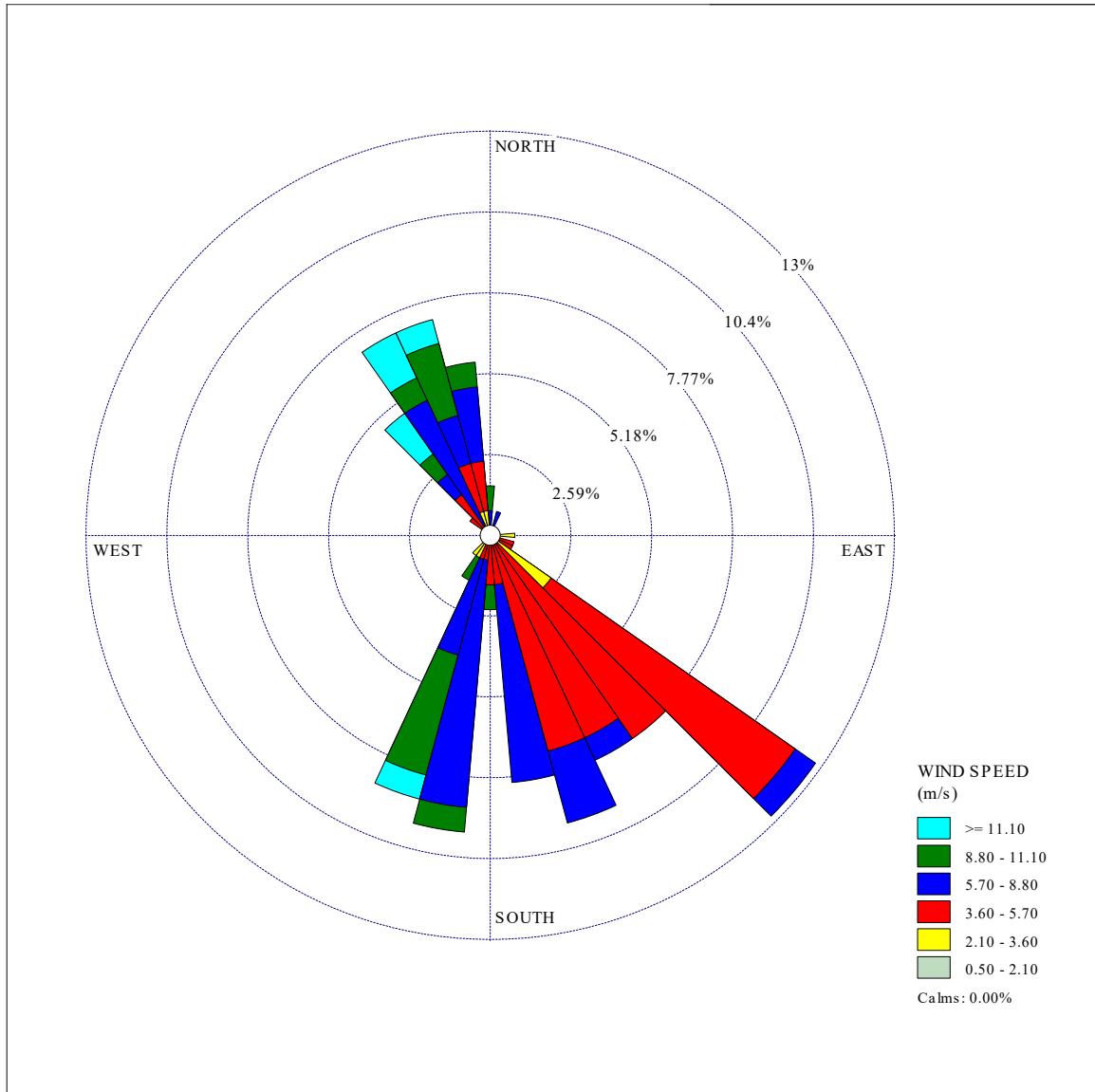
Time series showing wind direction (degrees) in blue and wind speed (m/s) in red at Utah Lake State Park from August 12th, 2024, to August 15th, 2024



Note. The yellow shaded regions are the times the sampling occurred.

Figure 18

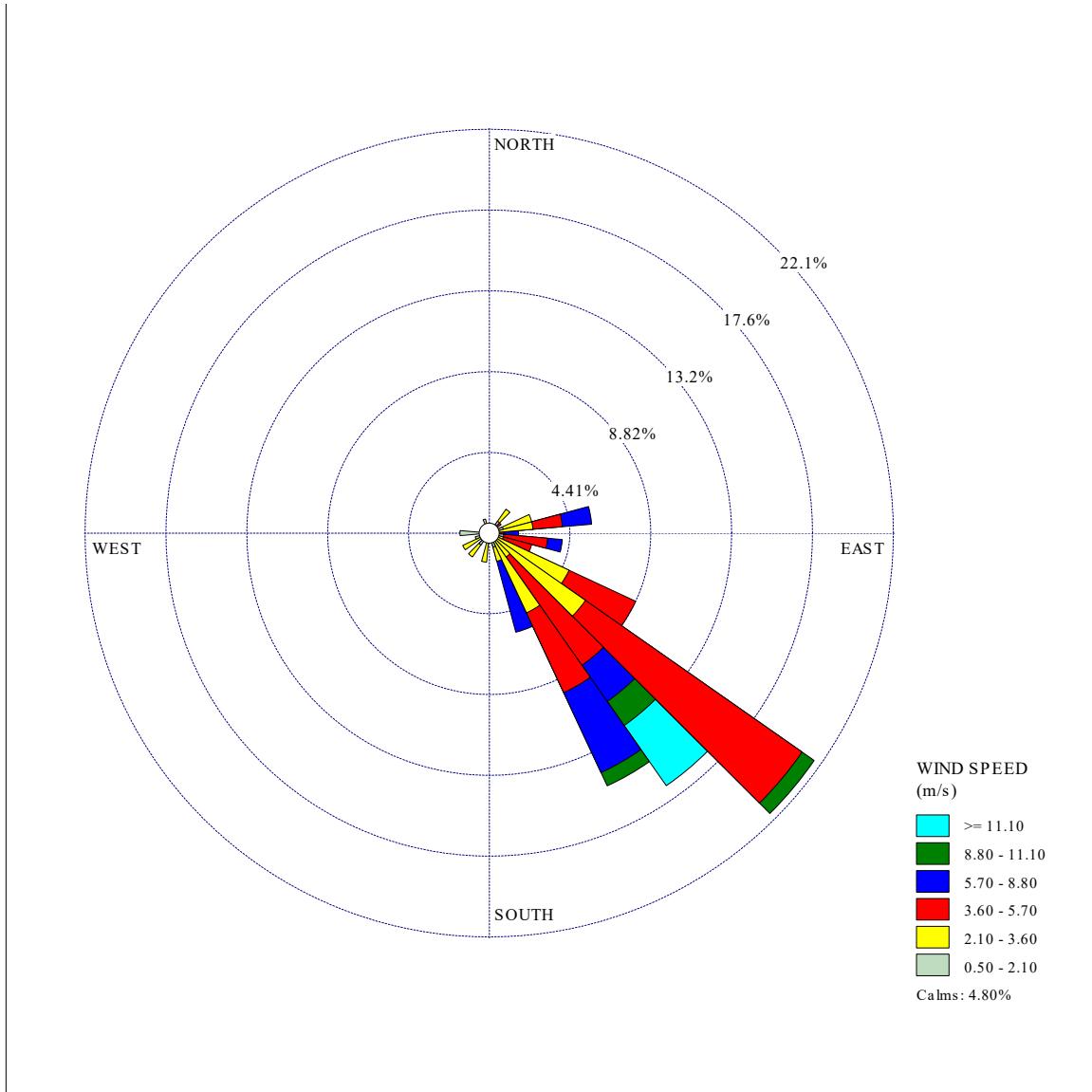
Wind rose diagram for Utah Lake State Park on Monday, August 12th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 6.30 m/s with a calm wind percentage of 0%. Most winds came from the southeast, with particularly intense winds maxing out at 13.4 m/s coming from both the southwest and the northwest.

Figure 19

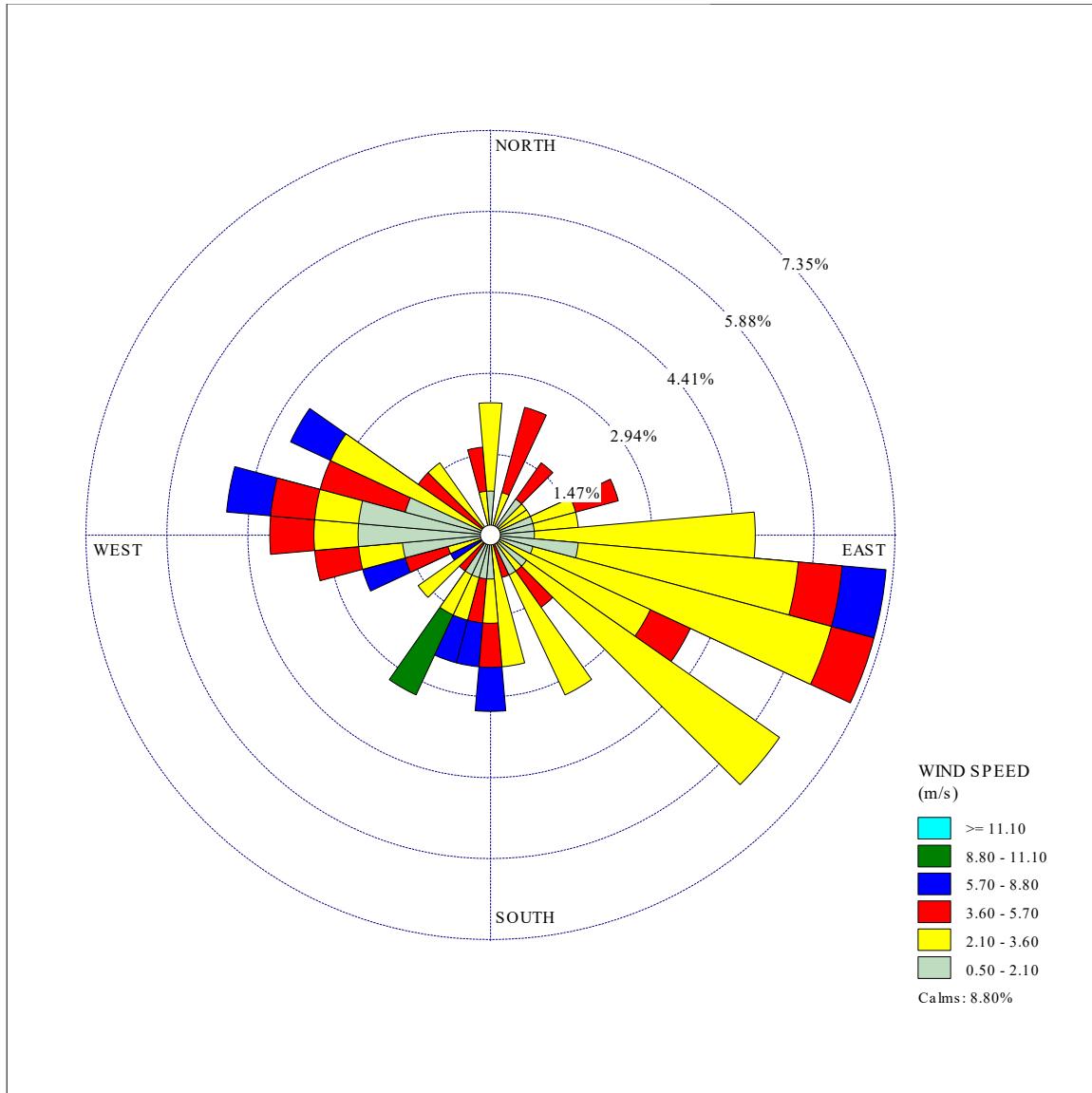
Wind rose diagram for Utah Lake State Park on Tuesday, August 13th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 4.30 m/s with a calm wind percentage of 4.80%. Most winds came from the southeast, with particularly intense winds maxing out at 12.9 m/s coming from the southeast as well.

Figure 20

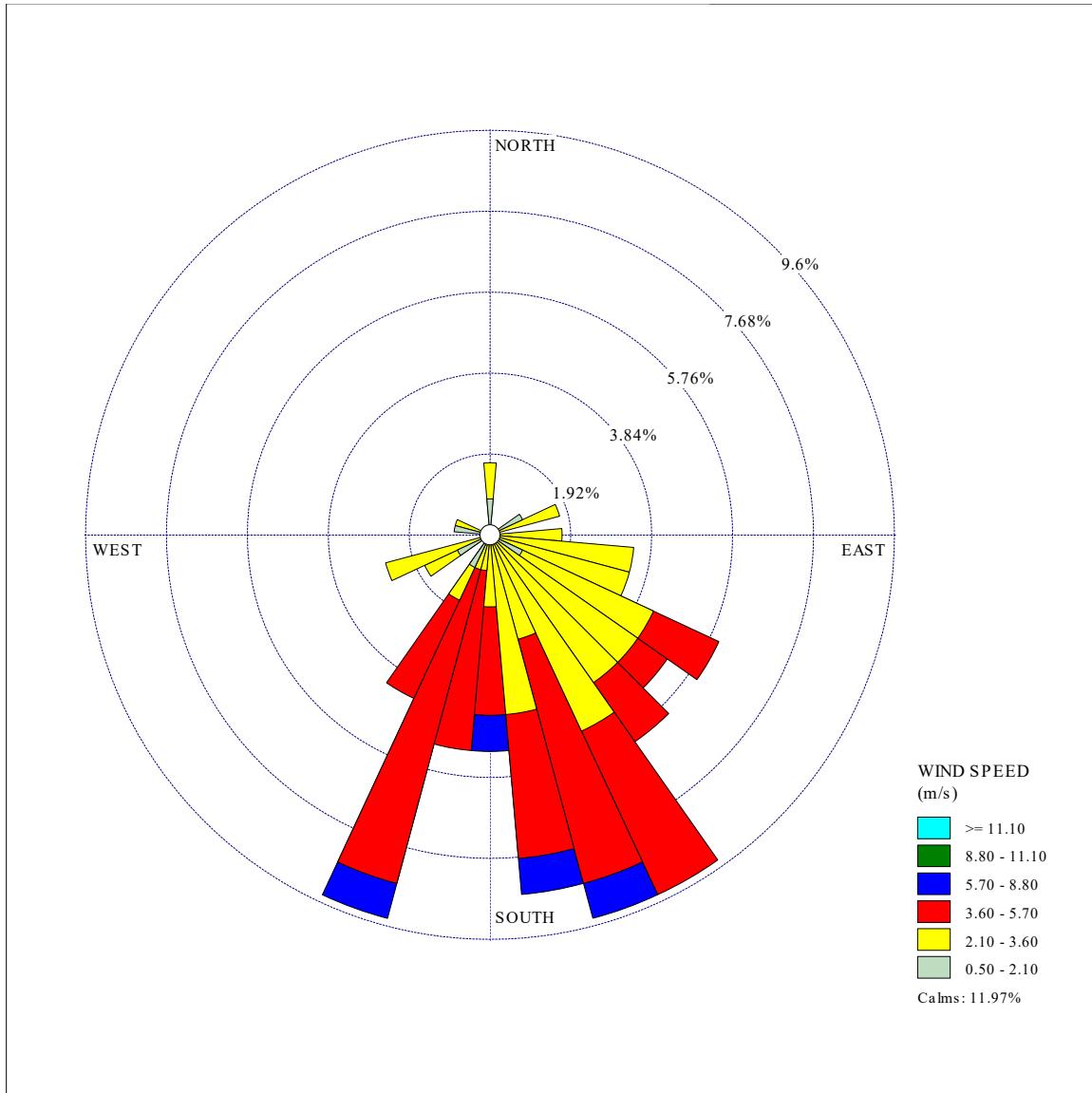
Wind rose diagram for Utah Lake State Park on Wednesday, August 14th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 2.79 m/s with a calm wind percentage of 8.80%. Most winds came from the southeast, with more intense winds coming from the southwest at 10.3 m/s.

Figure 21

Wind rose diagram for Utah Lake State Park on Wednesday, August 14th, 2024



Note. Data was collected from MesoWest Station ID KPVU. The average wind speed was 2.79 m/s with a calm wind percentage of 8.80%. Most winds came from the south with a max wind speed of 6.69 m/s.

4.2 Sample Collection

4.2.1. USV and Water Sampler

A Seafloor Systems EchoBoat-160 uncrewed surface vessel (USV) (Seafloor Systems, Inc., El Dorado Hills, California, United States), an autonomous robotic surveying boat, was used in conjunction with a custom-built water sampler to take water samples. The Echoboot-160 has a rough size of 1.7 meters in length by 0.8 meters in width and has two thrusters powered by four 14.8V lithium polymer batteries. The EchoBoat-160 allows for the collection of water samples away from the shore without the requirement for the ground team to take a row or motorized boat onto the water. The EchoBoat-160 also collects GPS data using an Emlid Reach RS2 Multi-Band RTK GNSS Receiver (Emlid, Budapest, Hungary), allowing the water samples to be matched to the locational data in geographic information software (GIS). The EchoBoat-160 has an onboard computer capable of being accessed by another computer via a remote desktop with the assistance of a MicroTik range extender (MicroTik, Riga, Latvia), so a separate computer on land was used to control both the Echoboot-160 and the water sampler; the onboard computer is powered by two 22.2V lithium polymer batteries. The boat is controlled using a FrSky Trananis Q X7 transmitter (FrSky, Wuxi, Jiangsu, China), while the water sampler is controlled from the Arduino software via serial port. Data about the boat can be obtained mid-run using a program called Mission Planner. The water sampler was made from a 12V 1.7A Water Pressure Pump Model SFDP1-012-035-21 (SeaFlo, South Bend, Indiana, United States), an Arduino Uno microcontroller (Arduino, Bangalore, Italy), and a DC motor (Figure 22 and Figure 23). Arduino and wiring setup were stored in a plastic Tupperware container on the boat to prevent the system from

getting wet. The water sampler has six bottles and, therefore, could collect six separate water samples per run. To prevent cross-contamination, the sampler flushes the system for 10 seconds before collecting another sample. The Arduino code and design files can be accessed from the USV-Automated-Water-Sampler GitHub repository (McPeake, 2025).

Figure 22

Water sampler and Arduino wiring setup in the Tupperware attached to the EchoBoat-

160

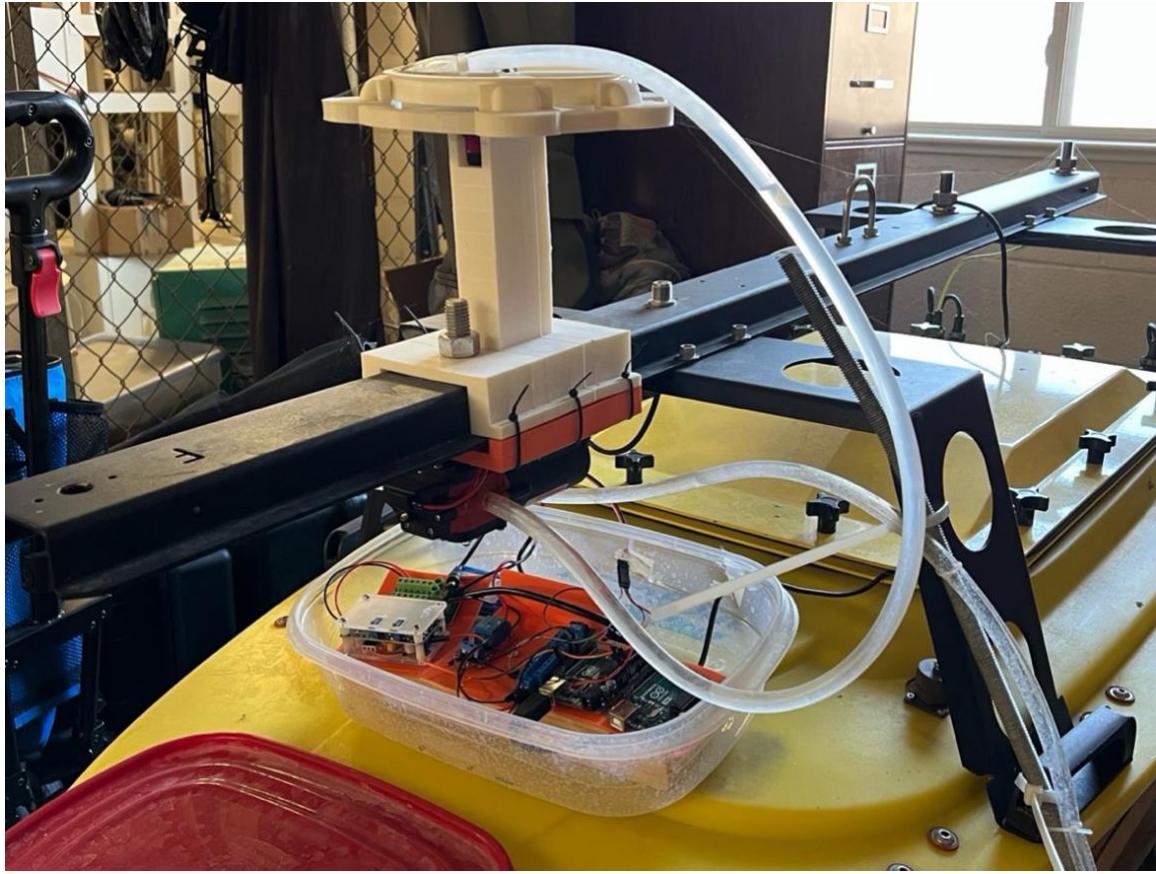
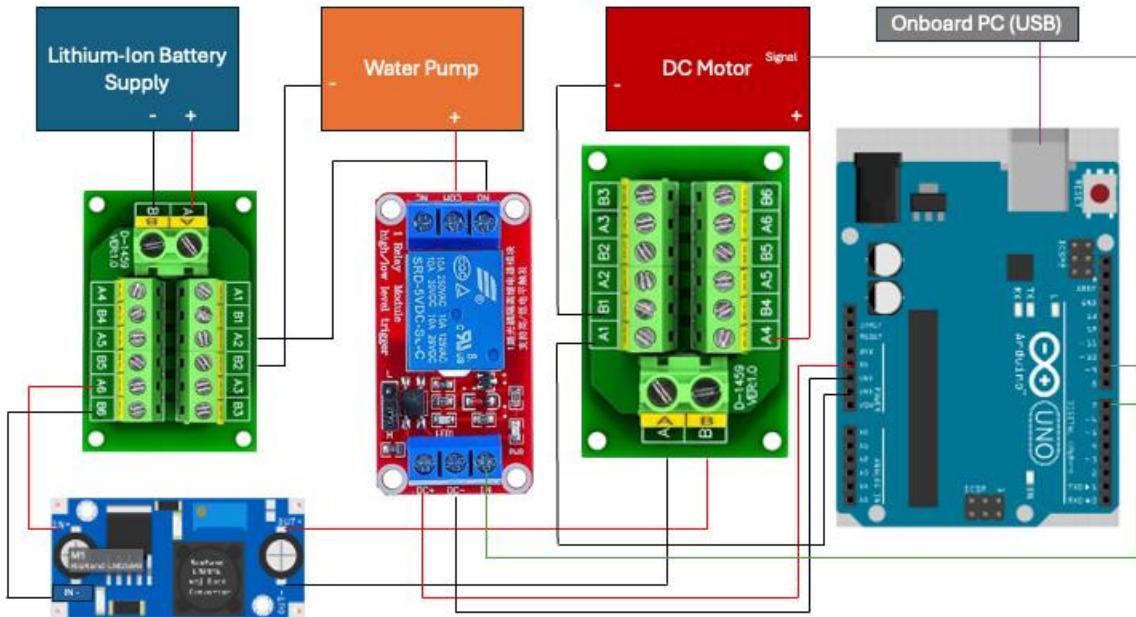


Figure 23

Wiring schematic for the Arduino-based water sampler



4.2.2. Water Samples

Two types of water samples were collected during each field campaign: discrete grab samples and composite water samples. While the collection methodologies are slightly different from the preliminary study described in section 3.1.1.3.1, the samples still used the same bottles and preservatives described there. Between the grab and composite samples, there were 12 water samples collected per day (9 grab, 3 composite), or 48 water samples per trip.

The grab samples were taken in triplicate at three separate locations every day between 11 am and 1 pm. Grab water samples were carefully collected from the water's surface to prevent the preservatives from being washed out any of the preservatives. Once collected, the water samples were placed into a cooler until they could be transferred to a refrigerator in the lab. The change from sampling three times per day at one location to

once per day at numerous locations was done to get a better understanding of microcystin concentrations throughout the campaign site. An example of water grab sampling can be seen in Figure 24.

Figure 24

A grab water sample being collected at Lincoln Marina



The composite samples were collected once a day, between 11 am to 1 pm, using the water sampler attached to the USV. The water sample would collect six 250 mL samples into six 250 mL screwcap bottles with no preservatives, and then all six samples were transferred into a two-liter screwcap bottle and mixed to create a single 1.5 L composite sample with no preservatives. From the 1.5 L composite sample, three 100 mL

samples with preservatives were created using three 150 mL amber screwcap bottles before they were placed into a cooler for storage. This provided three preserved composite samples per day, or 12 preserved composite samples per campaign. The samples remained in the cooler for the duration of the field campaign until they were transferred into a refrigerator in the lab. An example of composite water sampling using the USV can be seen in Figure 25.

Figure 25

The Echoboat-160 sampling along a transect to collect composite water samples at Lincoln Marina



In addition to the water samples, water quality data were recorded using a nke Instrumentation WiMo multiparameter sonde (nke Instrumentation, Hennebont, France) attached to the back of the boat using two L-brackets. The nke Instrumentation sonde was capable of recording timestamps, pressure (dbar), internal sonde temperature (°C),

conductivity (mS/cm), water temperature (°C), dissolved oxygen concentration (mg/L), dissolved oxygen saturation percent, chlorophyll-a (fluorescence or ppb), and phycocyanin (fluorescence or ppb). The sonde records a different parameter every second in a rotating order, meaning that each parameter is collected once every five seconds; the order of collecting is dependent on the order the sensors were placed. The sonde was only available for use for the Utah Lake State Park campaign.

4.2.3. Air Samples

The air sampling methodology shares its base with the methodology in the preliminary studies seen in section 3.1.1.3.2, with some modifications. Instead of using two MiniVols and one mid-Vol, nine MiniVols were spread out across the study area. The MiniVols draw air in at a flow rate of 6 to 7.5 L/min. The air samplers were placed on T-posts or tripods and ran approximately 10 hours per day, barring one day at Utah Lake State Park, August 12th, where high winds (13.4 m/s) and severe weather/rain forced the sampling to be cut short. One filter was used per air sampler per campaign for a total of nine air filter samples.

4.3 Sample Analysis

4.3.1. Water Samples

The water sample analysis methodology was unchanged from the preliminary study. See section 3.1.1.4.1 for water sample analysis methodology. It should be noted that all analyzed water samples qualified as Option A.

4.3.2. Air Samples

The air sample analysis methodology was unchanged from the preliminary study. See section 3.1.1.4.2 for air sample analysis methodology.

4.4 Fetch/Flex Footprints

The fetch/flux footprint/zone of influence (ZOI), or the areas that contribute emissions to the air samplers, was determined using meteorological data with Kljun et al.'s (2015) flux footprint prediction (FFP) model. The FFP model has inputs of canopy height (z_m), roughness length (z_0), mean horizontal wind speed (U_{mean}), boundary layer height (h), Monin-Obukhov length (L), standard deviation of lateral velocity fluctuations (σ_v), and friction velocity (u^*). Canopy height was determined to be four meters total: two meters from the water surface to the ground surface, and two meters from the ground surface to the top of the tripod/t-post. The FFP model can only use one of the roughness length or mean horizontal wind speed, so the wind speeds recorded from the Provo Airport MesoWest weather station were used as the mean horizontal wind speed. The boundary layer height was chosen to be 1,000 meters, as that is an approximation for a scenario at midday that is fully mixed (Nelson et al., 2021). The Monin-Obukhov length was approximated at -50 before 11:00 and after 16:00, and -100 between 11:00 and 16:00, as a Monin-Obukhov value less than zero corresponds to unstable conditions or a sunny midday scenario (Wikipedia, 2023). The standard deviation of lateral velocity fluctuations is the standard deviation of the horizontal wind speed. The friction velocity was approximated as 0.3 m/s (Large & Pond, 1981).

4.5 Quality Assurance and Quality Control

The quality assurance and quality control (QA/QC) protocols from the preliminary study were not changed. See section 3.1.1.5 for the QA/QC protocols.

CHAPTER 5

RESULTS

5.1 Lincoln Marina**5.1.1. Water Samples**

All field water samples had detectable concentrations for every microcystin congener (Figure 26A-B, Figure 27A-B; Table C1). When looking at all samples regardless of site collected or day of collection, MC-LR dominated and was the primary driver for the total microcystin concentration as the average sample had an MC-LR concentration of $1.91 \pm 5.74 \mu\text{g/L}$ with a range from $0.064 \mu\text{g/L}$ to $29.6 \mu\text{g/L}$, followed by MC-LW, MC-LF, MC-RR, MC-YR, MC-, and MC-LA (Table 13). MC-LA was the only microcystin congener not to be detected in every sample (17 of 48 samples registered $<0.001 \mu\text{g/L}$).

Table 13

Microcystin congener statistics at Lincoln Marina

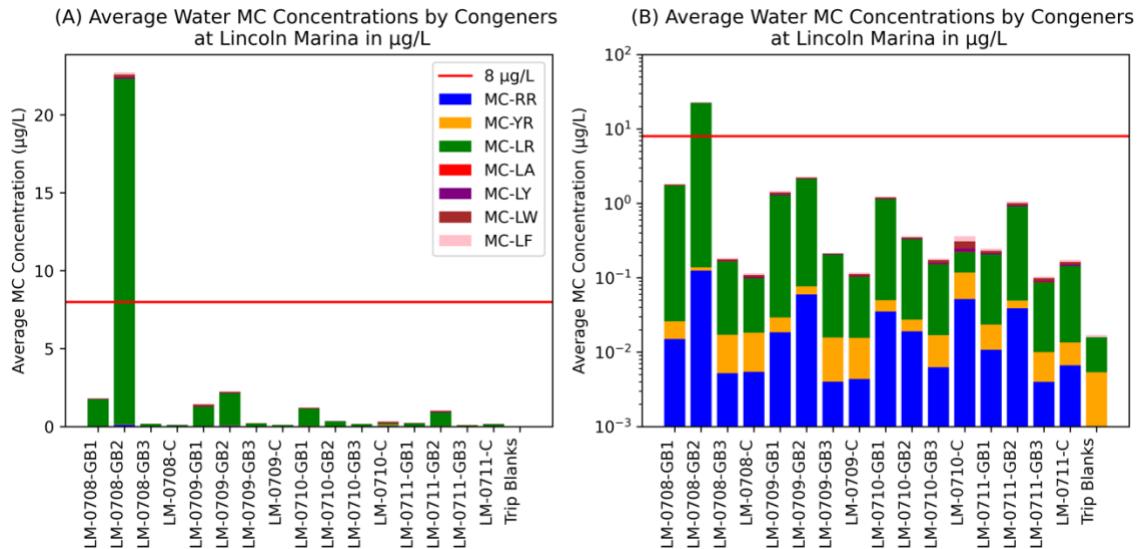
Statistics	MC-RR ($\mu\text{g/L}$)	MC-YR ($\mu\text{g/L}$)	MC-LR ($\mu\text{g/L}$)	MC-LA ($\mu\text{g/L}$)	MC-LY ($\mu\text{g/L}$)	MC-LW ($\mu\text{g/L}$)	MC-LF ($\mu\text{g/L}$)
Average \pm	$0.026 \pm$	$0.015 \pm$	$1.91 \pm$	$0.002 \pm$	$0.014 \pm$	$0.042 \pm$	$0.031 \pm$
SD	0.037	0.024	5.74	0.002	0.019	0.058	0.042
Max	0.142	0.175	29.6	0.009	0.079	0.240	0.164
Min	0.003	0.002	0.064	0.00	0.001	0.004	0.002

Single Factor ANOVA analysis ($\alpha = 0.05$) using log transformed values showed that day of collection was not a significant factor ($P\text{-value} = 0.168$), while site collected or grab sample ($P\text{-value} = < 0.001$) and site collected plus day of collection ($P\text{-value} = <$

0.001) was. Site collected plus the day of collection was more significant than just the site collected. Grab Sample 2 had the highest average total microcystin concentration across all sampling sites at $6.61 \pm 10.3 \text{ }\mu\text{g/L}$, with LM_0708_GB2 (Lincoln Marina, July 8th, Grab Sample 2) having the highest total microcystin concentration at $22.7 \pm 8.54 \text{ }\mu\text{g/L}$; LM_0708_GB2 was also the only sample that had a total microcystin concentration higher than the Utah Department of Environmental Qualities' (UDEQ) warning threshold of 8 $\mu\text{g/L}$ (Utah Department of Environmental Quality, 2025a). The site with the lowest average total microcystin concentration was Grab Sample 3 at $0.171 \pm 0.055 \text{ }\mu\text{g/L}$. The composite sample collected by the boat over the four days had an average total microcystin concentration of $0.297 \pm 0.515 \text{ }\mu\text{g/L}$ with a maximum value of 2.00 $\mu\text{g/L}$ and a minimum value of 0.103 $\mu\text{g/L}$. Single Factor ANOVA analysis ($\alpha = 0.05$) showed that the composite samples were not similar to Grab Sample 1 (P-value = < 0.001) nor Grab Sample 2 (P-value = < 0.001), but were similar to Grab Sample 3 (P-value = 0.640). The composite samples were unique in that the average concentration of MC-YR of the composite samples (0.024 $\mu\text{g/L}$) was double that of Grab Sample 1 (0.012 $\mu\text{g/L}$), Grab Sample 2 (0.012 $\mu\text{g/L}$), and Grab Sample 3 (0.010 $\mu\text{g/L}$). The average total microcystin concentration for the trip blanks was 0.017 $\mu\text{g/L}$, well below the field grab samples. The only congener to show in the trip blanks in order from largest concentration to lowest concentration was MC-LR (0.010 $\mu\text{g/L}$), MC-YR (0.005 $\mu\text{g/L}$), and MC-LF (0.001 $\mu\text{g/L}$).

Figure 26

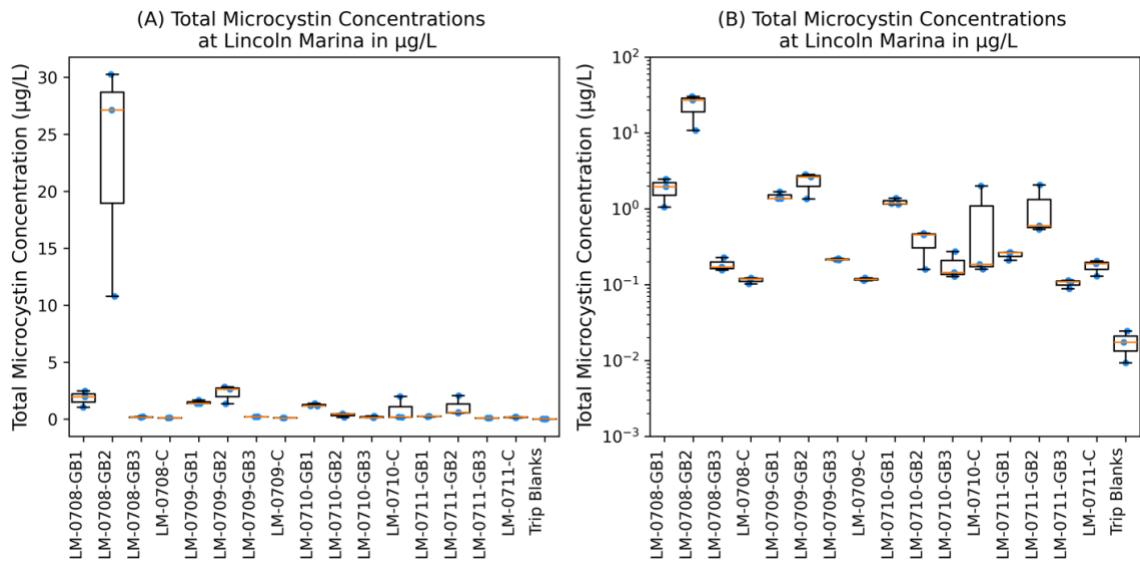
Stacked bar plot showing the individual congeners of microcystins and the total microcystin in µg/L for each grab sample (n = 3) and composited boat sample (n = 1) location and day of collection at Lincoln Marina on a (A) standard scale. (B) log scale



Note. Only LM-0708-GB2 (Lincoln Marina, July 8th, Grab Sample 2) recorded a concentration above the UDEQ warning threshold of 8 µg/L.

Figure 27

Box plots showing the distribution of triplicates for each grab sample location and day of collection in µg/L at Lincoln Marina on a (A) standard scale. (B) log scale

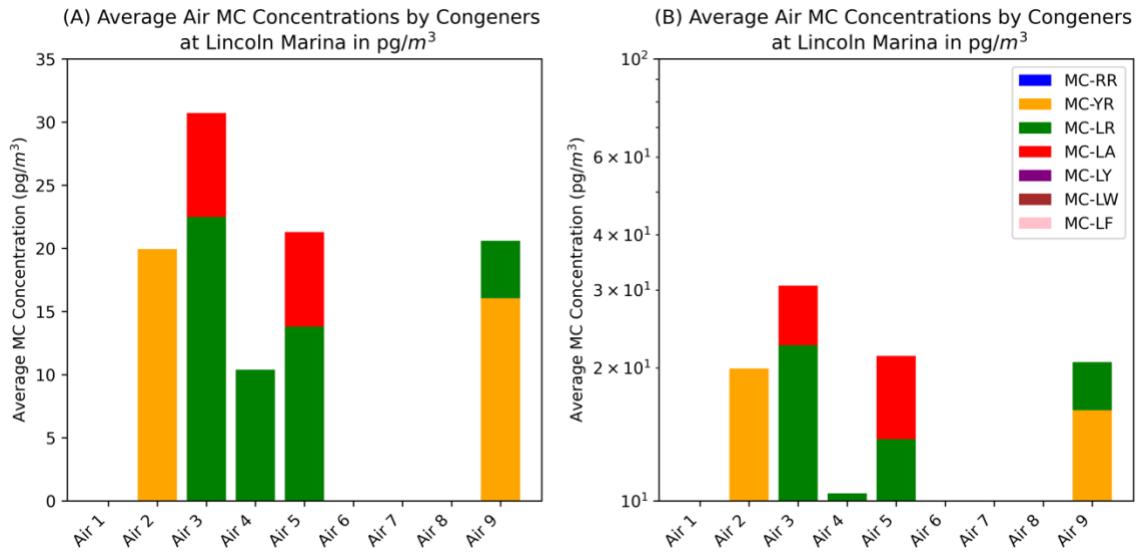


5.1.2. Air Samples

Five of the nine air filters had some detectable level of microcystins, ranging from 11.3 pg/m³ to 33.3 pg/m³ (Figure 28A-B, Table C2). The congener of microcystin varied between air samplers. MC-LR was the most common in the air samples found in four of the five detectable samples. The only other congeners found in the samples were MC-YR and MC-LA, which were each found in two of the five detectable samples; MC-RR, MC-LY, MC-LW, and MC-LF were not detected in any of the nine air samples. Air 2 was the only one to have detectable levels of microcystin that did not have any MC-LR concentration, only MC-YR.

Figure 28

Stacked bar plot showing the individual congeners of microcystins and the total microcystin in pg/m³ for each air sampler at Lincoln Marina on a (A) standard scale. (B) log scale



Note. Air 1, 6, 7, and 8 did not record microcystin concentrations above the detection limit.

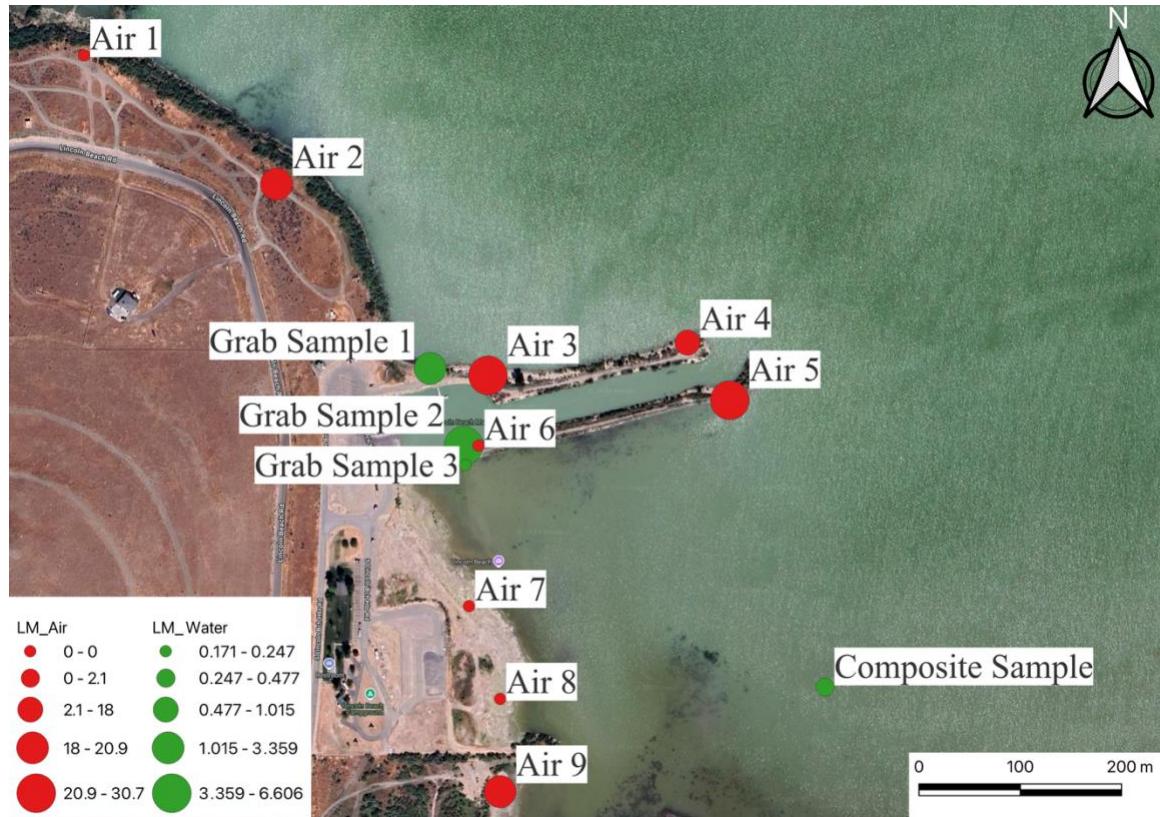
5.1.3. Air vs. Water Samples

A QGIS map showing sample locations and intensities for Lincoln Marina can be seen in Figure 29. The red circles represent total microcystin air sample concentrations from 0 pg/m³ to 33.3 pg/m³, while the green circles represent average total microcystin water sample concentrations from 0.171 µg/L to 6.61 µg/L. Generally, the higher concentrations for the air and water samples were found closer to the marina, but there are exceptions, such as Grab Sample 3 and Air 3, 4, and 5. There were some unique patterns regarding microcystin congeners. For the water samples, the average composite

sample MC-YR concentration (0.024 µg/L) was double the average MC-YR concentration of Grab Sample 1 (0.012 µg/L), Grab Sample 2 (0.012 µg/L), and Grab Sample 3 (0.010 µg/L), and were the only water sample not taken on shore. For the air samples, MC-YR was only found on the northern and southern edges of the study area, while MC-LA was exclusively found near the two arms of the marina. Three of the four non-detects were located away from the marina, with the other non-detect being located closest to the Lincoln Marina boat launch.

Figure 29

QGIS map of sample locations and intensities for the Lincoln Marina campaign from July 7th, 2024, to July 11th, 2024



Note. Water samples are represented in green in $\mu\text{g/L}$, while air samples are represented in red in pg/m^3 .

The air-to-water microcystin ratio was calculated by dividing the total microcystin concentration for each air sample by the average total microcystin water concentration ($2.07 \times 10^9 \text{ pg}/\text{m}^3$). Of the five air samples with detectable microcystin concentrations, the air-to-water ratios were between 10^{-8} and 10^{-9} , while the average air concentration (all nine air samples including non-detects) was 10^{-9} , and the average air detect concentration

(only the five detects) was 10^{-9} (Table 14). These air-to-water ratios are in line with the ratios seen in previous studies, which range from 10^{-8} to 10^{-13} (Labohá et al., 2023).

Table 14

Air-to-water Microcystin Ratios at Lincoln Marina

Sample	Total MC (pg/m ³)	Air/Water Ratio	Power of 10
Air 1	0.00	0.00	0
Air 2	19.9	9.64×10^{-9}	-9
Air 3	19.9	1.49×10^{-8}	-8
Air 4	10.4	5.05×10^{-9}	-9
Air 5	21.2	1.03×10^{-8}	-8
Air 6	0.00	0.00	0
Air 7	0.00	0.00	0
Air 8	0.00	0.00	0
Air 9	20.6	9.97×10^{-9}	-9
Average Air	11.4	5.53×10^{-9}	-9
Average Air Detect	20.6	9.96×10^{-9}	-9

Note. The average water microcystin concentration used was 2.07×10^9 pg/m³. The ratios seen for Lincoln Marina range from 10^{-8} to 10^{-9} , while the ratios seen in previous studies range from 10^{-8} to 10^{-13} (Labohá et al., 2023).

5.1.4. Fetch/Flux Footprint

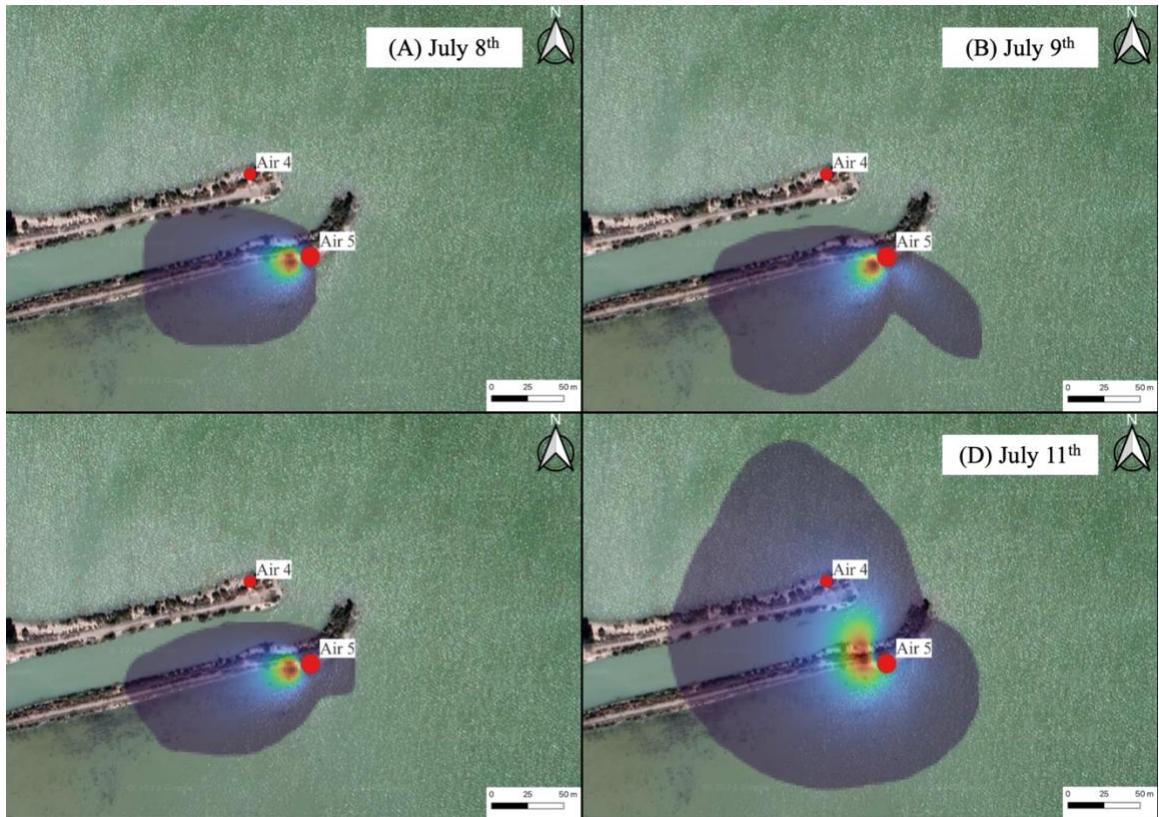
The fetch/flux footprint/zone of influence (ZOI) for each day at Lincoln Marina suggested that the most influence on microcystin aerosolization came from approximately 25-30 meters from the west (Figure 30A-D, Figure E1). All four days were similar in the sense that the farthest extent of the fetch in the west was about 150 meters and the farthest extent of the fetch in the south was about 60-80 meters. July 8th, July 9th, and July 10th had their farthest fetch in the north at about 20-30 meters, while July 11th had its furthest fetch in the north at around 150 meters. All days had some fetch coming from the

east/southeast, or off the lake, between 30-75 meters except for July 8th, which had less than 10 meters. July 11th had the largest ZOI, while July 8th and 9th had the smallest ZOIs.

Figure 30

Flux footprint overlayed on a QGIS map at Lincoln Marina on (A) July 8th, 2024. (B)

(C) July 10th, 2024. (D) July 11th, 2024



Note. All flux footprints are being overlaid as an example of the fetch at Air Sampler 5 but could be overlaid at any air sampler.

5.2 Utah Lake State Park

5.2.1. Water Samples

All field water samples had detectable concentrations for at least one microcystin congener (Figure 31A-B, Figure 32A-B, Table D1). When looking at all samples regardless of site collected or day of collection, MC-LR was the most dominant congener and the primary driver for the total microcystin concentration as the average sample had an MC-LR concentration of $0.013 \pm 0.011 \mu\text{g/L}$ with a range from $0.005 \mu\text{g/L}$ to $0.081 \mu\text{g/L}$, followed by MC-YR, and MC-RR (Table 15). While MC-YR had a higher average concentration than MC-RR, MC-YR was only found in 38 of 48 samples, while MC-RR was found in 47 of 48 samples. MC-LA, MC-LY, MC-LW, and MC-LF were the least common congeners, and all had average concentrations around $0.001 \mu\text{g/L}$ and were not commonly found in the samples.

Table 15

Microcystin congener statistics at Utah Lake State Park

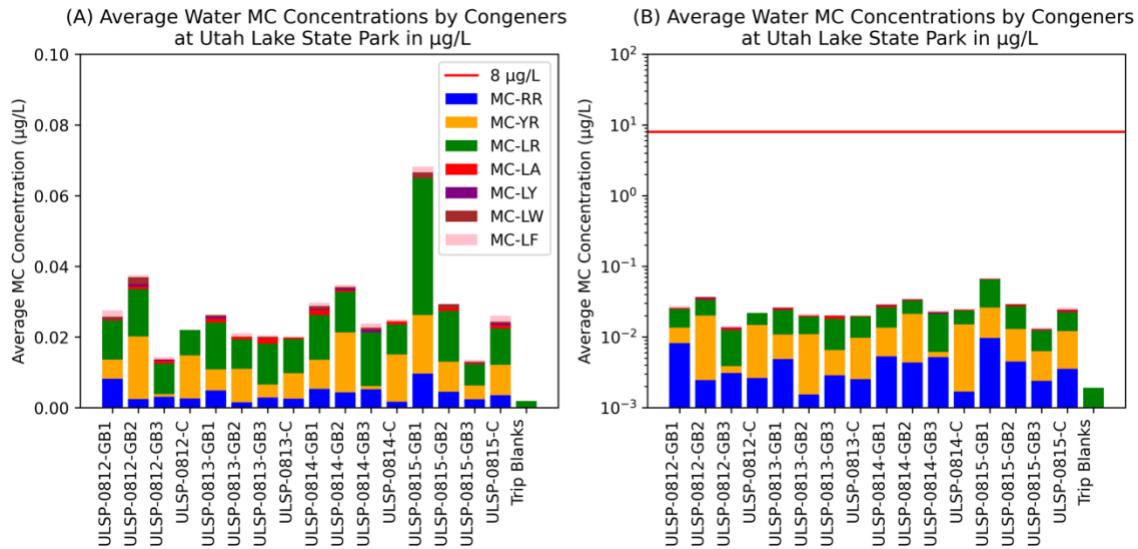
Statistics	MC-RR ($\mu\text{g/L}$)	MC-YR ($\mu\text{g/L}$)	MC-LR ($\mu\text{g/L}$)	MC-LA ($\mu\text{g/L}$)	MC-LY ($\mu\text{g/L}$)	MC-LW ($\mu\text{g/L}$)	MC-LF ($\mu\text{g/L}$)
Average	0.004 ± 0.003	0.009 ± 0.008	0.013 ± 0.011	0.001 ± 0.001	$< 0.001 \pm 0.001$	0.001 ± 0.001	0.001 ± 0.001
\pm SD							
Max	0.018	0.037	0.081	0.003	0.002	0.004	0.004
Min	0.00	0.00	0.055	0.001	0.00	0.00	0.00

Single Factor ANOVA analysis ($\alpha = 0.05$) using log transformed values showed that day of collection was not a significant factor ($P\text{-value} = 0.600$), while site collected or grab sample ($P\text{-value} = 0.002$) and site collected plus day of collection ($P\text{-value} = 0.013$) were. The site collected was more significant than site collected plus day of

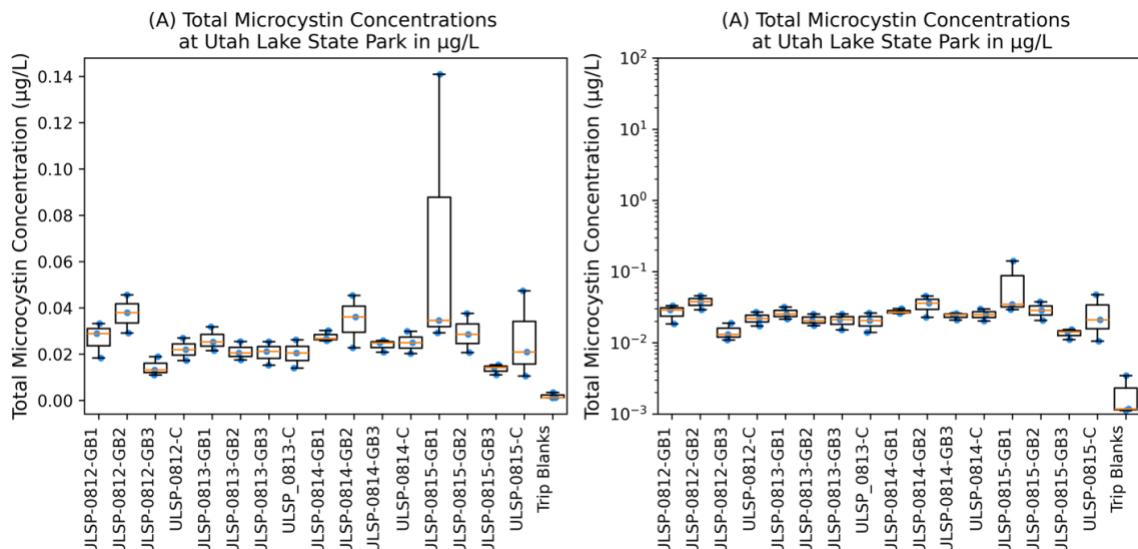
collection. Grab Samples 1 and 2 had the highest average total microcystin concentrations at $0.037 \pm 0.032 \mu\text{g/L}$ and $0.031 \pm 0.009 \mu\text{g/L}$ respectively, with ULSP_0815_GB1 (Utah Lake State Park, August 15th, Grab Sample 1) having the highest total microcystin concentration at $0.068 \pm 0.051 \mu\text{g/L}$; no samples had a total microcystin concentration higher than the UDEQ's warning threshold of 8 $\mu\text{g/L}$ (Utah Department of Environmental Quality, 2025a). The lowest average total microcystin concentration, ignoring the trip blanks, was Grab Sample 3 at $0.018 \pm 0.005 \mu\text{g/L}$. The composite sample had an average total microcystin concentration of $0.023 \pm 0.009 \mu\text{g/L}$, with a maximum concentration of $0.047 \mu\text{g/L}$ and a minimum concentration of $0.011 \mu\text{g/L}$. Single Factor ANOVA analysis ($\alpha = 0.05$) showed that the composite samples were not similar to Grab Sample 1 (P-value = 0.062) nor Grab Sample 2 (P-value = 0.059) but were similar to Grab Sample 3 (P-value = 0.112). The average total microcystin concentration for the trip blanks measured $0.002 \mu\text{g/L}$, well below the field grab samples. The only congener to show in the trip blanks was MC-LR.

Figure 31

(A) Stacked bar plot showing the individual congeners of microcystins and the total microcystin in $\mu\text{g/L}$ for each grab sample location and day of collection at Utah Lake State Park on a (A) standard scale. (B) log scale

**Figure 32**

Box plots showing the distribution of triplicates for each grab sample location and day of collection in $\mu\text{g/L}$ at Utah Lake State Park on a (A) standard scale. (B) log scale

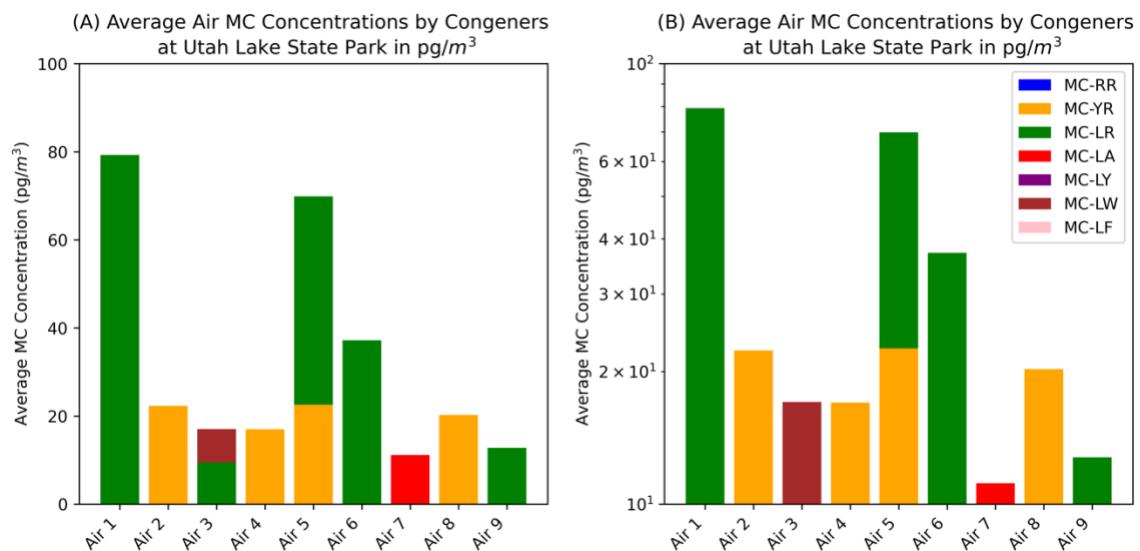


5.2.2. Air Samples

All air filters had some detectable level of microcystins, ranging from 12.1 pg/m³ to 85.7 pg/m³, with six of the nine samples having concentrations below 25 pg/m³ (Figure 33A-B, Table D2). The congener of microcystin varied between air samplers. MC-LR is the most common in the air samples found in five of the nine samples. The second most common congener was MC-YR, which was found in four of the nine samples. MC-LA and MC-LW are found in one of the nine samples each. MC-RR, MC-LY, and MC-LF were not found in any of the nine air samples. Outside of air samples Air 3 and 5, each air sample only had one detectable congener of microcystin; Air 3 had MC-LR and MC-LW, while Air 5 had MC-LR and MC-YR.

Figure 33

Stacked bar plot showing the individual congeners of microcystins and the total microcystin in pg/m³ for each air sampler at Utah Lake State Park on a (A) standard scale. (B) log scale



5.2.3. Air vs. Water Samples

A QGIS map showing sample locations and intensities for Utah Lake State Park can be seen in Figure 34. The red circles represent total microcystin air sample concentrations from 11.2 pg/m³ to 79.3 pg/m³, while the green circles represent average total microcystin water sample concentrations from 0.018 µg/L to 0.037 µg/L. There are no discernible patterns regarding total microcystin or microcystin congeners and water sample locations. There is a possible pattern for the total microcystins air sampler concentrations, as the samplers with the highest concentrations (Air 1, 2, 5, and 6) are in the path that the boats would take to get from the marina to the lake. There weren't any discernible patterns regarding microcystin congeners and air sampler location.

Figure 34

QGIS map of sample locations and intensities for the Utah Lake State Park campaign from August 12th, 2024, to August 15th, 2024



Note. Water samples are green in $\mu\text{g/L}$, while air samples are red in pg/m^3 .

The air-to-water microcystin ratio was calculated by dividing the total microcystin concentration for each air sample by the average total microcystin water concentration ($2.73 \times 10^7 \text{ pg}/\text{m}^3$). The total microcystin concentration air-to-water ratio for the nine air samples ranged from 10^{-6} to 10^{-7} , while the average air concentration was 10^{-6} (Table 16). These air-to-water ratios are greater than the range for air-to-water ratios seen in other studies, which range from 10^{-8} to 10^{-13} (Labohá et al., 2023).

Table 16

Air-to-water Microcystin Ratios at Utah Lake State Park

Sample	Total MC (pg/m ³)	Air/Water Ratio	Power of 10
Air 1	79.3	2.90×10^{-6}	-6
Air 2	22.3	8.18×10^{-7}	-7
Air 3	17.1	6.24×10^{-7}	-7
Air 4	17.0	6.21×10^{-7}	-7
Air 5	69.9	2.56×10^{-6}	-6
Air 6	37.2	1.36×10^{-6}	-6
Air 7	11.2	4.09×10^{-7}	-7
Air 8	20.3	7.42×10^{-7}	-7
Air 9	12.8	4.68×10^{-7}	-7
Average Air	31.9	1.17×10^{-6}	-6

Note. The average water microcystin concentration used was 2.73×10^7 pg/m³. The ratios seen for Utah Lake State Park range from 10^{-6} to 10^{-7} , while the ratios seen in previous studies range from 10^{-8} to 10^{-13} (Labohá et al., 2023)

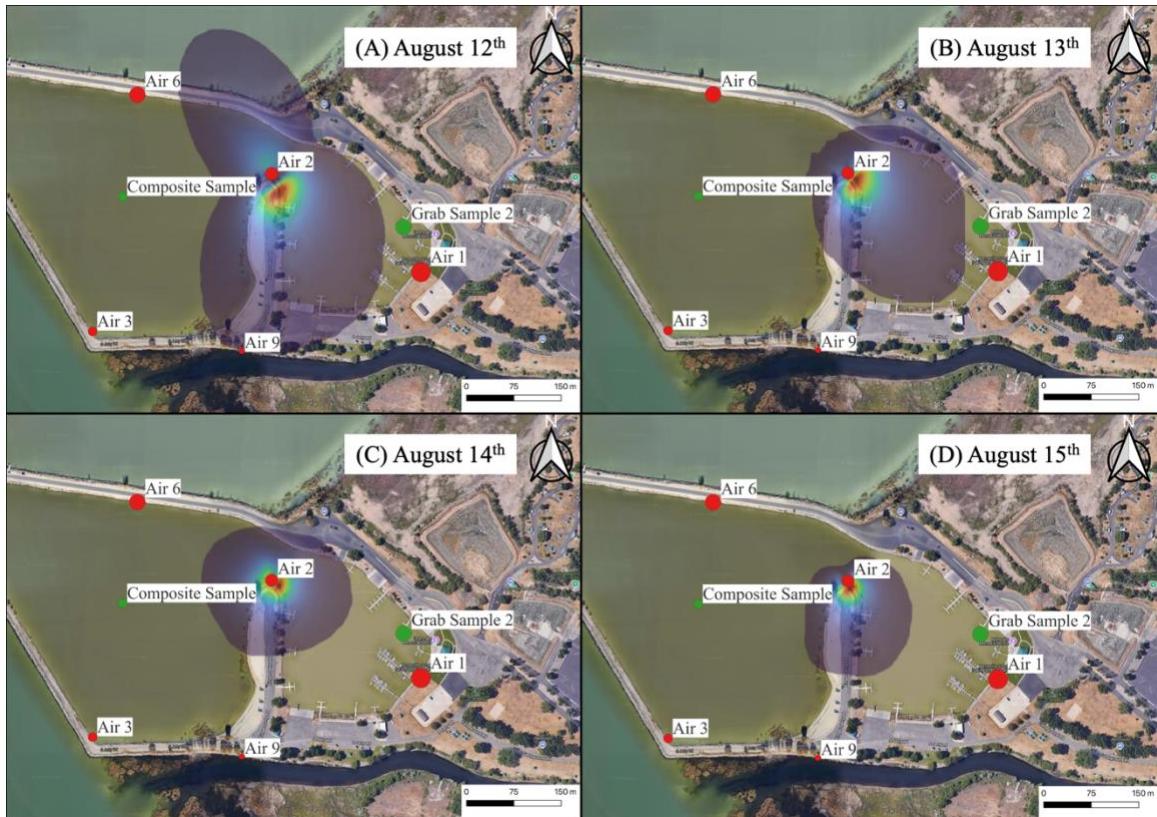
5.2.4. Fetch/Flux Footprint

The fetch/flux footprint/ZOI for each day at Utah Lake State Park suggested that the most influence on microcystin aerosolization came from approximately 25-50 meters from the southeast, with August 14th having some significant fetch 25 meters from the west/southwest (Figure 35A-D, Figure E2). August 12th had its farthest extent of influence approximately 300 meters from the northwest, 300 meters from the south, 100 meters from the west, and 150 meters from the east. August 13th had its farthest extent of influence 250 meters from the southeast and 150 meters to the east; there was also some influence 75 meters from the west and 100 meters from the northwest. August 14th had a similar farthest extent of influence approximately 100-125 meters in all four cardinal directions. August 15th had the farthest extent of influence 150 meters from the south,

with other influence 75 meters from the west, 100 meters from the east, and 30 meters from the north. August 12th had the largest ZOI, while August 15th had the smallest ZOI.

Figure 35

Flux footprint overlayed on a QGIS map at Utah Lake State Park on (A) August 12th, 2024. (B) August 13th, 2024. (C) August 14th, 2024. (D) August 15th, 2024



Note. All flux footprints are being overlaid as an example of the fetch at Air Sampler 2 but could be overlaid at any air sampler

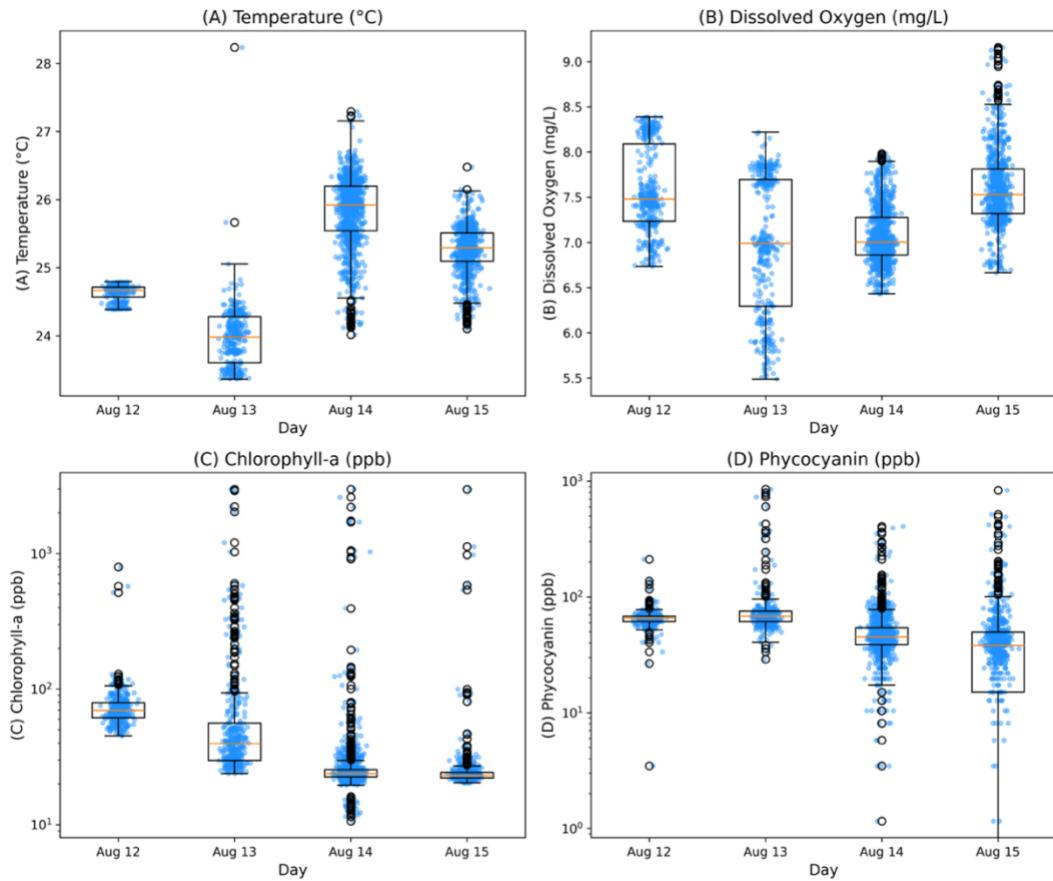
5.2.5. Water Quality Parameters

Boxplots showing daily distributions of temperature (°C), dissolved oxygen (mg/L), chlorophyll-a (ppb), and phycocyanin (ppb) can be seen in Figure 36A-D, while

the daily averages with standard deviations, medians, minimums, maximums, and ranges can be seen in Table 17. The time of collection for the data was in the afternoon, during the same time that the grab samples were collected. The total time collected is different for each day, as August 12th had 32 minutes of data, August 13th had 32 minutes of data, August 14th had 1:27 hours of data, and August 15th had 1:00 hour of data. The water temperature and dissolved oxygen concentrations are typical of what one would see in a water body without extreme algal bloom infestations. The chlorophyll-a and phycocyanin concentrations suggested that there are considerable amounts of plant life in the water body, although that does not mean that the plant life is necessarily algal blooms.

Figure 36

Boxplots showing (A) temperature ($^{\circ}\text{C}$) data, (B) dissolved oxygen (mg/L) data, (C) chlorophyll-a (ppb) data in log scale, and (D) phycocyanin (ppb) data in log scale at Utah Lake State Park from August 12th, 2024, to August 15th, 2024



Note. Data was taken around 11 am and 1 pm every day.

Table 17

Daily averages, standard deviations, medians, minimums, maximums, and ranges for temperature (°C), oxygen concentration (mg/L), oxygen saturation (%), chlorophyll-a (ppb), and phycocyanin (ppb) at Utah Lake State Park from August 12th, 2024, to August 15th, 2024

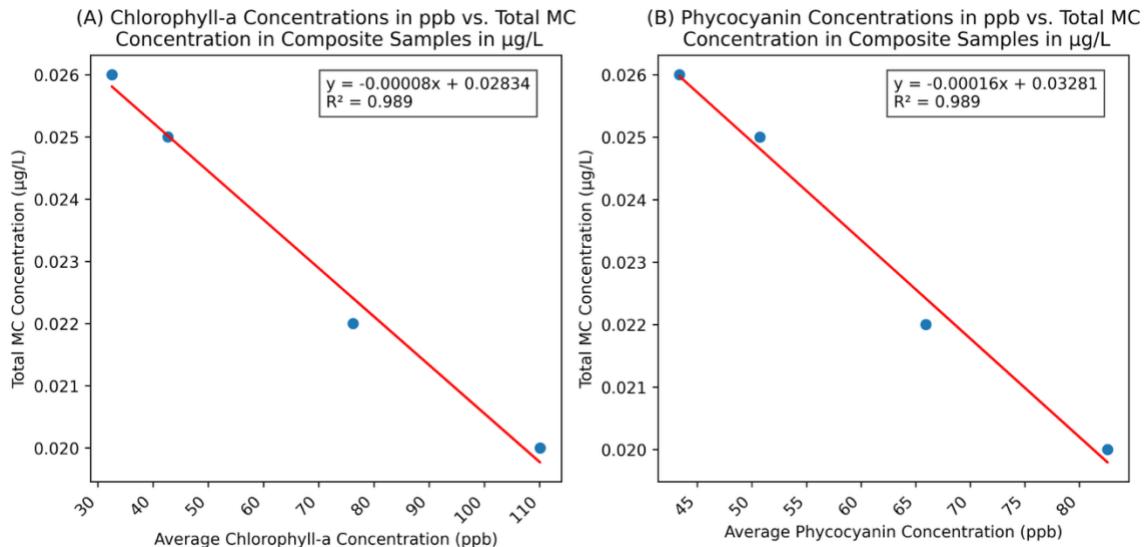
August 12 th , 2024 / Elapsed Time: 0:32					
Stats	Temperature (°C)	Oxygen Concentration (mg/L)	Oxygen Saturation (%)	Chlorophyll-a (ppb)	Phycocyanin (ppb)
Average	24.6 ± 0.117	7.58 ± 0.467	92.0 ± 5.58	76.2 ± 52.5	65.9 ± 12.3
Median	24.7	7.48	91.2	69.5	65.9
Min	24.4	6.73	81.6	45.2	3.47
Max	24.8	8.39	101	795	211
Range	0.411	1.66	19.9	750	208
August 13 th , 2024 / Elapsed Time: 0:32					
Stats	Temperature (°C)	Oxygen Concentration (mg/L)	Oxygen Saturation (%)	Chlorophyll A (ppb)	Phycocyanin (ppb)
Average	24.0 ± 0.429	6.99 ± 0.748	84.4 ± 7.84	110 ± 317	82.6 ± 86.6
Median	24.0	6.99	83.9	39.6	68.3
Min	23.4	5.49	71.3	23.8	28.9
Max	28.2	8.22	98.6	2980	852
Range	4.88	2.74	27.3	2960	824
August 14 th , 2024 / Elapsed Time: 1:27					
Stats	Temperature (°C)	Oxygen Concentration (mg/L)	Oxygen Saturation (%)	Chlorophyll A (ppb)	Phycocyanin (ppb)
Average	25.8 ± 0.516	7.07 ± 0.306	87.4 ± 3.41	42.7 ± 177	50.7 ± 34.5
Median	25.9	7.00	87.1	23.8	45.1
Min	24.0	6.43	79.9	10.6	0.00
Max	27.3	7.98	97.9	2980	407
Range	3.28	1.55	18.0	2970	407
August 15 th , 2024 / Elapsed Time: 1:00					
Stats	Temperature (°C)	Oxygen Concentration (mg/L)	Oxygen Saturation (%)	Chlorophyll A (ppb)	Phycocyanin (ppb)
Average	25.3 ± 0.343	7.60 ± 0.425	93.3 ± 5.06	32.6 ± 126	43.4 ± 60.8
Median	25.3	7.53	92.2	22.9	38.2
Min	24.1	6.67	83.2	0.00	0.00
Max	26.5	9.16	113	2970	835
Range	2.38	2.49	29.5	2970	835

5.2.5.1. Composite Water Samples vs. Water Quality Parameters

The composite sample for each day was compared with the average chlorophyll-a and phycocyanin concentrations of the corresponding day to determine if noticeable trends were associated with chlorophyll-a or phycocyanin concentrations and total microcystin concentrations. Trends showed that as the chlorophyll-a or phycocyanin concentrations increased, the total microcystin concentrations decreased (Figure 37A-B). The trendline between chlorophyll-a and total microcystin concentration has an equation of $y = -0.00008x + 0.0283$ and an R^2 of 0.989, while the trendline between phycocyanin and total microcystin concentration has an equation of $y = -0.0002x + 0.0328$ and an R^2 value of 0.989.

Figure 37

(A) Scatter plot comparing the daily average chlorophyll-a concentrations in ppb vs. the daily total MC concentrations of the composite samples in $\mu\text{g/L}$. (B) Scatter plot comparing the daily average phycocyanin concentrations in ppb vs. the daily total MC concentrations of the composite samples in $\mu\text{g/L}$.



Note. The chlorophyll-a regression line has an equation of $y = -0.00008x + 0.0283$ and an R^2 value of 0.989. The phycocyanin regression line has an equation of $y = -0.0002x + 0.0328$ and an R^2 value of 0.989

5.3 Comparisons Between Campaign Sites

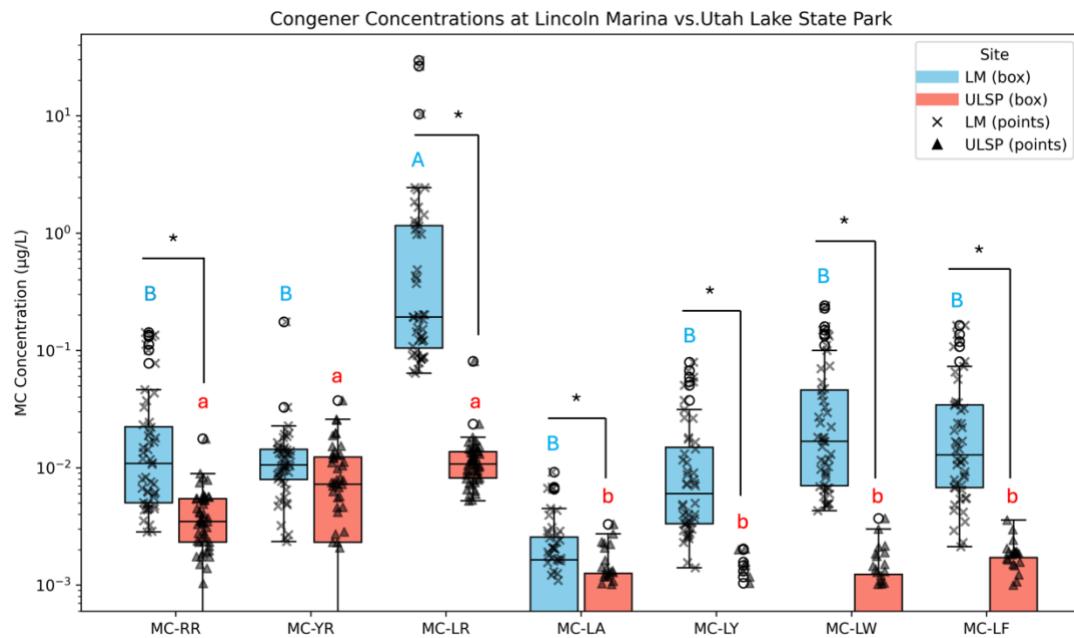
5.3.1. Water Samples

The total microcystin concentrations in the water samples at Lincoln Marina were larger than the total microcystin concentrations at Utah Lake State Park (P -value = 0.018, $\alpha = 0.05$) (Figure 38, Table C1, Table D1). The Tukey post-hoc test was performed after the Single Factor ANOVA analysis to determine the significance of all congeners across a

single campaign site and both campaign sites. For Lincoln Marina, only MC-LR is significantly different from the other congeners. At Utah Lake State Park, MC-RR, MC-YR, and MC-LR are significantly different from other congeners, while MC-LA, MC-LY, MC-LW, and MC-LF are not. Between both sites, every congener is significantly different from its pair at the other site except for MC-YR.

Figure 38

Boxplots with individual datapoints comparing congener concentrations at Lincoln Marina in blue vs. Utah Lake State Park in red



Note. Tukey post-hoc was performed to show differences between congeners and campaigns, noted using the letters and * sign. Capital letters represent Lincoln Marina, lowercase letters represent Utah Lake State Park, and the * sign shows a significant difference between campaign sites. Different letters indicated a significant difference.

5.3.2. Air Samples

The total microcystin concentration in the air samples at Utah Lake State Park were larger than the total microcystin concentrations at Lincoln Marina (P -value = 0.045, $\alpha = 0.05$) (Figure 28A-B, Figure 33A-B, Table C2, Table D2). Five of the nine filters registered microcystins at Lincoln Marina, while all nine filters registered microcystins at Utah Lake State Park. MC-LR, MC-YR, and MC-LA were found at both campaign sites, while MC-LW was found only at Utah Lake State Park; MC-RR, MC-LY, and MC-LF were found at neither campaign site.

CHAPTER 6

DISCUSSION

The objectives of this project were to (i) develop a methodology for analyzing cyanobacteria/microcystins in air samples, (ii) collect and analyze air samples from Utah Lake to determine if microcystins are present in the air at detectable limits, and (iii) build and test an autonomous unoccupied vehicle (UV) as an alternative method for collecting cyanobacteria harmful algal bloom (cHAB) water samples.

6.1 Water Samples

The water samples for Lincoln Marina had higher concentrations of total microcystins compared to Utah Lake State Park; total microcystin concentration statistics for the water samples between the two campaigns can be seen in Table 18. Total microcystin concentrations were significantly higher at Lincoln Marina than Utah Lake State Park; Single Factor ANOVA analysis ($\alpha = 0.05$) supports that the two campaign datasets are significantly different ($P\text{-value} = 0.018$). Congener-wise, MC-LR was the dominant congener, and MC-LA was the least common congener for both Lincoln Marina and Utah Lake State Park in terms of both concentration and prevalence. MC-LR, being the dominant congener, aligns with prior knowledge and research (US EPA, 2024; Utah Department of Environmental Quality, 2025a, 2025b). Looking at the concentrations and prevalence in samples, in addition to Tukey post-hoc tests, MC-LR was more prevalent than every other congener at Lincoln Marina, while MC-RR, MC-YR, and MC-LR were more prevalent than every other congener at Utah Lake State Park. MC-YR and MC-RR were more prevalent in Utah Lake State Park compared to Lincoln Marina, while MC-LF,

MC-LW, and MC-LY were more prevalent in Lincoln Marina compared to Utah Lake State Park.

Table 18

Total microcystin concentration statistics in µg/L between Lincoln Marina and Utah Lake State Park

Total MC Statistic	Lincoln Marina (µg/L)	Utah Lake State Park (µg/L)
Average	2.04 ± 5.86	0.027 ± 0.019
Maximum	30.3	0.141
Minimum	0.088	0.011

6.1.1. USV Sampler Effectiveness

The results showed that the UV with a custom water sampler could collect cHAB water samples that were representative of some sampling sites (Table 19). The study does not have grab and composite sample concentrations for the same location, so direct comparisons cannot be made between traditional grab and automated sampling methods. Single Factor ANOVA analysis ($\alpha = 0.05$) showed that while the composite water samples were significantly different from the samples taken at Grab Sample sites 1 and 2 for both Lincoln Marina and Utah Lake State Park, the composite samples were significantly similar to the samples taken at Grab Sample 3 for both campaign sites. This revelation becomes more interesting as for Lincoln Marina, where the most similar or closest physical site to the composite sample is Grab Sample 3; there was no site close to or similar to the composite sample at Utah Lake State Park. When focusing on the congeners, the only unique trend is that the composite sample for Lincoln Marina had double the MC-YR concentration compared to the Lincoln Marina grab samples; this was not seen at Utah Lake State Park. This could be because the composite samples were

taken off-shore versus the grab samples being on-shore. Another possible explanation could be that the composite sample for Lincoln Marina was taken on the lake, while the composite sample for Utah Lake State Park was taken confined in the left side of the marina. This could be remedied in future studies by taking grab samples at the same location as the composite samples for a direct comparison.

Table 19

P-values when comparing the composite site water samples vs. the three-grab sample site water samples using Single Factor ANOVA analysis

Site Comparison	Lincoln Marina	Utah Lake State Park
Composite vs. GB1	< 0.001	0.062
Composite vs. GB2	< 0.001	0.059
Composite vs. GB3	0.640	0.112

Note. $\alpha = 0.05$. The composite site samples were significantly different from Grab Samples 1 and 2 for both Lincoln Marina and Utah Lake State Park but were significantly similar to Grab Sample 3 for both campaign locations.

The USV sampler did run into some issues while sampling, the two notable issues being that the USV sampler only had a range of 400 meters from the transmitter/base camp and that the USV's movement could be hindered heavily by algae mats. The USV could only be operated approximately 400 meters from the transmitter/base camp before the connection began to drop. This could be fixed by moving the transmitter/base camp to a central location within range of all desired sampling locations or moving the transmitter/base camp around as the USV runs. Transmitter range was not a limitation for this study but could be for a study with a greater distance between water samplers. At Utah Lake State Park, which contained several underwater algae mats, it wasn't

uncommon for algae to get stuck in the USV's propellers and severely limit movement speed. This can be avoided by not running into algae mats, but it can be difficult to avoid them if the USV operator cannot see the mats. There is one additional logistics downside to the UV boat, that being that there is still the possibility of microcystin exposure due to droplets getting splashed on the boat and bottle. The UV was implemented to help prevent human samplers from coming into contact with microcystins, but the UV greatly reduces that chance, as contact with droplets on the boat and sample bottles can mostly be prevented with basic preventative measures such as gloves and clothes fully covering the skin.

6.2 Air Samples

This study showed that it is possible to detect microcystins in the air at Utah Lake; the developed methodology for collecting and analyzing microcystin air samples was valid. Table 20 compares the ranges and averages of the total microcystins in the air for previous research studies compared to this study in pg/m³. For this study, Lincoln Marina had an average air concentration of 11.4 ± 11.3 pg/m³ and a range from 0.00 pg/m³ to 30.7 pg/m³, while Utah Lake State Park had an average air concentration of 31.9 ± 24.0 pg/m³ and a range from 11.2 pg/m³ to 79.3 pg/m³. The aerosolized microcystin concentrations at Lincoln Marina and Utah Lake State Park were similar to aerosolized microcystin concentrations seen in other studies. Congener-wise, microcystins in air samples were driven by MC-LR, similar to water samples. MC-YR, MC-LA, and MC-LW were also detectable in smaller concentrations, with the other three congeners (MC-RR, MC-LF, and MC-LY) not present in detectable amounts; MC-LW was only found at Utah Lake State Park. Single Factor ANOVA analysis ($\alpha = 0.05$) showed that the Lincoln

Marina and Utah Lake State Park air samples were significantly different (P-value = 0.045).

Table 20

Summary of averages and ranges of total microcystin air concentrations of previous studies compared to this study at Lincoln Marina (LM) and Utah Lake State Park (ULSP) in pg/m³

Study	Location	Microcystin Air Concentration (pg/m ³)
This Study	Utah, USA	LM Average: 11.4 ± 11.3 LM Range: 0.00 – 30.7 ULSP Average: 31.9 ± 24.0 ULSP Range: 11.2 – 79.3
Backet et al., 2008	Michigan, USA	Day 1 Average: 80 ± 90 Day 1 Range: 5 – 319 Day 2 Average: 70 ± 14 Day 2 Range: 20 – 456 Day 3 Average: <LOD Day 3 Range: <LOD Day 1 Lake 1 Average: 400 ± 750 Day 1 Lake 1 Range: 0.00 – 2900
Backer et al., 2010	California, USA	Day 2 Lake 2 Average: 100 ± 230 Day 2 Lake 2 Range: 0.00 – 800 Day 3 Lake 2 Average: 200 ± 170 Day 3 Lake 2 Range: 0.00 – 400 Walker Pond Average: 91.81 ± 11.46
Carter, 2022	Massachusetts, USA	Walker Pond Range: 57.39 – 165.90 Lower Mill Pond Average: 73.27 ± 8.75 Lower Mill Pond Range: 51.51 – 128.08
Cheng et al., 2007	Michigan, USA	Day 1 Average: 80 ± 90 Day 2 Average: 70 ± 14 Day 3 Average: 0.0 ± 0.0
Gambaro et al., 2012	Venice, Italy	Range: 0.093 – 0.909
Labohá et al., 2023	Czech Republic	Range: 0.0570 – 0.414
Langley, 2019	NH/Mass., USA	Range: 0.930 – 3.79
Murby and Haney, 2015	ME/NH/Mass., USA	Range: 13.0 – 384
Shi et al., 2023	Ohio, USA	Max: 156 Lake Forsyth 12hr Average: 0.73 ± 0.64 Lake Forsyth 12hr Range: 0.14 – 1.62
Wood and Dietrich, 2011	New Zealand	Lake Forsyth 24hr Average: 0.023 ± 0.005 Lake Forsyth 24hr Range: 0.02 – 0.03 Lake Rotorua 24hr 1: 0.03 Lake Rotorua 4hr: 0.18 Lake Rotorua 24hr 2: 0.9

The air concentrations found in this study were similar to those found in previous studies. Some studies had averages and ranges of aerosolized microcystins larger than this study (Backer et al., 2008, 2010; Carter, 2022; Murby & Haney, 2015), while other studies had averages and ranges much smaller than this study (Labohá et al., 2023; Langley, 2019; Shi et al., 2023; Wood & Dietrich, 2011). There is no clear reason for the differences in microcystin concentrations between studies. Water concentrations could be a factor influencing airborne microcystin concentrations, but high water concentrations were found in conjunction with both high (Backer et al., 2008, 2010; Carter, 2022; Shi et al., 2023) and low microcystin air concentrations (Labohá et al., 2023; Langley, 2019). Recreation or water agitation is a variable factor, as Backer et al. (2008, 2010) sampled areas with high rates of recreation and agitation recorded high air microcystin concentrations, while Labohá et al. (2023) used a machine in the water near the air samplers to continuously agitate the water and recorded the lower air microcystin concentrations compared to other studies. Carter (2022) and Murby & Haney (2015) sampled directly above the water and recorded high air microcystin concentrations, while Langley (2019) did the same and recorded lower air microcystin concentrations. The effects of bloom conditions are also variable, as Backer et al. (2008, 2010) sampled directly in active algal blooms and recorded high air microcystin concentrations, while Labohá et al. (2023), Langley (2019) , and Wood & Dietrich (2011) did the same and recorded lower air microcystin concentrations. Weather may play a variable role; Backer et al. (2008, 2010) had wind and weather similar to this study (mostly less than 5 m/s) but with higher air microcystin concentrations, while Wood & Dietrich (2011) reported lower air concentrations with higher wind speeds up to 10.55 m/s. It could be possible that too

high wind speeds can negatively affect microcystin aerosolization or collection efficiency. However, it should be noted that Wood & Dietrich (2011) believe that the lower aerosolized microcystin concentrations despite high wind speeds are due to the type of nozzles they used for their air samplers rather than the wind itself, suggesting that wind is an important factor for higher microcystin aerosolization.

It should be noted, however, that Labohá et al. (2023) were able to show that for several studies focused on aerosolized microcystins (including theirs), the ratio of air concentrations to water concentrations ranged from 10^{-8} to 10^{-13} . So, while the aerosolized microcystin concentration may be lower relative to other studies, they are similar relative to the amount of microcystin in the water for each study. The air-to-water ratios for this study, when compared to their defined range, further confirm the idea that the air concentrations in this study are similar to those found in other studies and therefore are reasonable. For this study, the Lincoln Marina air-to-water ratios ranged from 10^{-8} to 10^{-9} , while the Utah State Lake Park air-to-water ratios ranged from 10^{-6} to 10^{-7} . The Lincoln Marina ratios fall in line with the higher end of the established range, while the Utah Lake State Park ratios are 10 to 100 times greater than the established range.

6.2.1. Air Sample Collection and Analysis

For the collection methodology, this study used low-volume samplers, Teflon filters, on-shore sampling, multiple samplers, and a daily sampling length of approximately 10 hours (falls within the 2-12 hour parameter defined in Table 1). Outside of the use of a Teflon filter, this study's collection methodology was similar to a number of previous studies. The usage of high-volume or low-volume air samplers varies;

however, previous work using high-volume air samplers (Backer et al., 2008, 2010; Cheng et al., 2007; Labohá et al., 2023; Wood & Dietrich, 2011) and low-volume air samplers (Carter, 2022; Langley, 2019; Murby & Haney, 2015; Shi et al., 2023; Wood & Dietrich, 2011) combined with this study's preliminary trial campaign in October 2024 showed that both high- and low-volume samplers can be used with similar results. Most of the previous studies used on-shore sampling and multiple air samplers. The main difference between collection methodologies was the type of filter used, with all filter types giving similar results. For the analysis methodology, this study used LC/MS, sonicated samples, filtered samples, dried samples under N₂, reconstituted or resuspended dried samples, and concentrated samples. The usage of ELISA vs. LC/MS/MS varied between studies; however, previous results using ELISA (Backer et al., 2008, 2010; Carter, 2022; Cheng et al., 2007; Langley, 2019; Murby & Haney, 2015; Wood & Dietrich, 2011) and LC/MS (Backer et al., 2008, 2010; Labohá et al., 2023; Shi et al., 2023; Wood & Dietrich, 2011) compared to the results presented in this thesis show that researchers could use either method with similar results, provided the method is paired with the correct pre-analysis steps. The analysis methodology used in this thesis was similar to the other studies that used LC/MS/MS, with the only major exception being that most previous studies cut up the filters as part of their analysis methodology, while this study did not.

The blank air samples do raise some concern, as there were samples where MC-LR concentrations on the blank filters read higher than MC-LR concentrations on the field filters. For Lincoln Marina, the average MC-LR concentration on the three blank filters was greater than the detectable concentration of five of the nine field sample

concentrations; this is concerning, given that blank filters should be near zero. One possible explanation for this is that the LC/MS/MS is mistakenly identifying another compound as MC-LR. The usage of double mass spectrometry should reduce the possibility of another compound being mistaken for MC-LR, but it still could be possible. While the MC-LR concentration could not be explained, steps were taken to mitigate this issue by subtracting the detectable microcystin congener concentrations on the blank air filters from the microcystin congener concentrations on the field air filters.

6.3 Factors that Influence Microcystins in Air and Water

Cyanotoxins can aerosolize when a disturbance or turbulence occurs within the water body, dislodging the cyanotoxin from the water and into the air above. Possible disturbances in the water include crashing waves, water recreation, high wind speeds, and raindrops from storm events (Cheng et al., 2007; May et al., 2017; Wiśniewska et al., 2019). One of the biggest factors influencing the aerosolization of cyanotoxins is the amount of cyanotoxins in the water, which is a direct result of factors such as temperature and sunlight. Chlorophyll-a and phycocyanin have been shown to have a positive correlation with microcystin concentrations (Douglas Greene et al., 2021; Francy et al., 2016, 2020; Kotak et al., 1995; Lehman, 2007; Marion et al., 2012; Oh et al., 2001; Singh et al., 2015; Smith et al., 2024; Zhang et al., 2017). Once the cyanobacteria become airborne, numerous factors such as air mass advection, wind speed and direction, humidity, temperature, and rainfall can affect how the aerosolized cyanobacteria travel (Lewandowska et al., 2017). The ratio of cyanotoxins in the air to the cyanotoxins in the water has been shown to range between 10^{-8} to 10^{-13} (Labohá et al., 2023).

Table 21 shows the ranges of the total microcystin concentrations in the air and water compared to weather and water parameters for Lincoln Marina and Utah Lake State Park. The total water concentrations at Lincoln Marina were significantly greater than the total water concentrations at Utah Lake State Park (P -value = 0.018), while the total air concentrations at Utah Lake State Park were significantly greater than Lincoln Marina (P -value = 0.045). This is further shown using the air-to-water ratios, as the air-to-water ratios at Utah Lake State Park are 10 to 100 times greater than Lincoln Marina. High wind speeds were established as a major driver of microcystin aerosolization, and this study supports that claim. At Lincoln Marina, the 4-day peak wind speed occurred on the final day (July 11th) at 7.72 m/s, while the other three days didn't have a wind speed above 5 m/s. At Utah Lake State Park, the 4-day peak wind speed occurred on the first day (August 12th) at 13.4 m/s, a wind speed so intense that it caused that day's sampling to be cut short by two hours. Two of the other three days had peak wind speeds above 10 m/s, while the fourth and final day had a peak wind speed of 6.69 m/s, greater than all but one day at Lincoln Marina. For Lincoln Marina, outside of some weaker winds on July 9th, none of the wind came from the ideal wind direction, or off the lake towards the land. For Utah Lake State Park, the most intense winds for August 12th, August 14th, and August 15th came from off the lake towards the land. Utah Lake State Park had better wind conditions for microcystin aerosolization and greater microcystin aerosolization compared to Lincoln Marina. The air-to-water ratio of Utah Lake State Park, being 10 to 100 times greater than Lincoln Marina, reinforces the idea that wind speed is a major factor in microcystin aerosolization. These results further reinforce prior knowledge that wind speed is a major driving factor for general spray aerosol production (Bruch et al.,

2021; Markuszewski et al., 2024; Revell et al., 2021; Saliba et al., 2019). The data also showed that temperature wasn't a major factor in microcystin aerosolization but could be argued to be important for microcystin concentration in water. While Lincoln Marina and Utah Lake State Park had similar temperature ranges and the same 4-day max of 32.0 °C, the 4-day average temperature at Lincoln Marina (31.1 °C) was 4.5 °C higher than Utah Lake State Park (26.6 °C).

When comparing the chlorophyll-a and phycocyanin concentrations to the total microcystins concentrations in the composite samples at Utah Lake State Park, both parameters showed a negative correlation. The trendline between chlorophyll-a and total microcystin concentration has an equation of $y = -0.00008x + 0.0283$ and an R^2 of 0.989, while the trendline between phycocyanin and total microcystin concentration has an equation of $y = -0.0002x + 0.0328$ and an R^2 value of 0.989. These results differ from what is commonly observed, as most studies show a positive correlation between chlorophyll-a and phycocyanin when compared to microcystin concentrations (Douglas Greene et al., 2021; Francy et al., 2016, 2020; Kotak et al., 1995; Lehman, 2007; Marion et al., 2012; Oh et al., 2001; Singh et al., 2015; Smith et al., 2024; Zhang et al., 2017). Possible explanations as to why these results differ from most studies are that this study had a limited sample pool of four samples, a limited variety of data at only one campaign site and time, and lower microcystin concentrations in the water paired with lots of non-microcystin plant life. This study had issues at Utah Lake State Park where algae got caught in the boat's thrusters and impaired travel, which pairs well with the claim of non-algae plant life in the boat's path.

Table 21

Comparisons between the ranges of total microcystins concentrations across all sites in air and water, air-to-water ratios, weather conditions, and water parameters between Lincoln Marina and Utah Lake State Park

Parameter	Lincoln Marina	Utah Lake State Park
Water Concentration ($\mu\text{g/L}$)	0.088 – 30.3	0.011 – 0.141
Air Concentration (pg/m^3)	0.00 – 30.6	11.2 – 79.3
Air/Water Ratio	$0.00 – 1.49 \times 10^{-8}$	$4.09 \times 10^{-7} – 2.90 \times 10^{-6}$
Temperature ($^\circ\text{C}$)	22.0 – 32.0	19.0 – 32.0
Wind Speed (m/s)	0.00 – 7.72	0.00 – 13.4
Chlorophyll-a (ppb)	N/A	0.00 – 2980
Phycocyanin (ppb)	N/A	0.00 – 852

Another consideration is that three air samplers that had the highest microcystin concentrations at Lincoln Marina (Air 3, 4, and 5) and four air samplers that had the highest microcystin concentrations at Utah Lake State Park (Air 1, 2, 5, and 6) were in line with the path that motorized boats used to get from the respective marinas to the lake (Figure 29 and Figure 34). This corresponds to a potential mechanism of water surface disturbances and wave crashing influencing cyanotoxin aerosolization (Cheng et al., 2007; May et al., 2017; Wiśniewska et al., 2019). The one exception for Lincoln Marina is Air 6, which was the closest sampler to the Marina but was a non-detect at $0 \text{ pg}/\text{m}^3$. Generally, the farther away from the boat paths, the lower the microcystin air concentrations. The only exceptions to that pattern were Air 2 and Air 9 at Lincoln Marina and Air 8 at Utah Lake State Park. Topography could potentially be the reason for Lincoln Marina's Air 2 concentrations, as it was located at a higher elevation unobstructed by vegetation, but Lincoln Marina Air 1 was located in a similar place,

slightly more northwest, and was a non-detect. Lincoln Marina Air 9 and Utah Lake State Park Air 8 were located near marshy or wetland areas, teaming with vegetation.

6.3.1. Fetch/Flux Footprint

The fetch/flux footprint/zone of influence (ZOI) for each day of sampling corresponded with the wind roses for each sampling day; the dominant directions seen in the wind roses were the dominant directions seen in the flux footprints. The dominant winds for both campaign sites came off land towards the lake, so the most influential zones of the ZOI were in the direction of the land. The ZOI was correlated with the wind speeds; as the wind speed increased, the distance the ZOI covered increased. This was most seen when comparing the Lincoln Marina ZOIs to the Utah Lake State Park ZOIs; Utah Lake State Park had higher wind speeds and bigger ZOIs. The correlation was stronger in the less influential zones of the footprint where the footprint could increase by 100-150 meters, as the most influential zones of the footprint only increased by 20 meters with higher wind speeds. This shows that while microcystin concentrations farther away from the air sampler can influence the microcystin concentrations collected by the sampler, the microcystin concentrations closest to the air sampler will be the most influential. This suggests that the best place to take microcystin water samples to compare to microcystin air samples would be within 25-50 meters of the air samplers, further proving the point that air samplers need to be placed on the shore or near water. It should be noted that these flux footprint prediction (FFP) models do not consider water/air concentration or emissions strength, just metrological/atmospheric conditions; this is something that could be remedied in future studies.

6.4 Broader Implications

Microcystins have been shown to be in the water and air at Utah Lake. Microcystins in the water are known to be a threat to human and animal health, but their health effects in air are less documented (Arman & Clarke, 2021; Lopez et al., 2008; US EPA, 2024; Utah Department of Environmental Quality, 2025b). Yoshida et al. (1997) have shown that studies in mice suggest that nasally applied microcystins may have the same toxicity as orally applied microcystins and that microcystins could have a 10 times higher availability via inhalation when compared to oral ingestion. Current World Health Organization (WHO) guidelines have a limit of 1 µg/L MC-LR (World Health Organization, 2022), meaning a human could consume 2 µg MC-LR per day, assuming an adult consumes 2 liters of water per day. Considering the potential 10 times higher availability in air, Wood and Dietrich (2011) hypothesized that the maximum daily inhaled concentration (MDIC) should be around 200 ng MC-LR or 4.58 ng MC-LR/m³ (4580 pg/m³), assuming that human breathes in between 30.3 to 72.3 L/min. This study found that air concentration ranged from 0.00 ng/m³ to 0.031 ng/m³ (Average: 0.011 ± 0.011 ng/m³) at Lincoln Marina and 0.011 ng/m³ to 0.079 ng/m³ (Average: 0.032 ± 0.024 ng/m³) at Utah Lake State Park, which is below the MDIC proposed by Wood and Dietrich. It should be noted that these estimates are based on the average amount of air and water a human adult consumes alongside MC-LR limits, not long-term epidemiology studies.

6.5 Limitations

There were limitations with this study, mostly driven by time and financial constraints. The first limitation was that water samples were not collected multiple times

a day to test for temporal trends similar to the preliminary study. Having data to see how the microcystin concentrations in the water change over the day would help determine if a particular time of the day is more dangerous than others. The preliminary study showed some potential trends for October, but these trends could be different in the earlier months of the bloom season. Determining microcystin trends over a single day was not the goal of this study and it was a conscious choice to sample once at multiple sites versus multiple times at one site, but it could provide interesting information for future studies.

The second limitation was that the spatial resolution of the water samples was insufficient to determine their contributions to the concentrations in the air at each location. Each air sample has a ZOI, which was only calculated after the field campaigns. Determining the ZOI before field sampling would allow for water samples to be paired with air samples. This still has its limitations, however, as the ZOIs are heavily dependent on wind speed and direction, which can't be predicted in advance. It would be possible to use historical meteorological/amphoteric conditions at a site to predict what the ZOIs could be, but it's not a guarantee that it will be. The results from this study showed that 25-50 meters from the air sample would be an ideal place to take water samples, but that could change with different weather conditions. The third limitation was that boundary layer height, Monin-Obukhov length, and friction velocity needed to run the FFP model could not be calculated due to insufficient high-level atmospheric data, meaning they had to be approximated. While there is a good amount of quality research showing reasonable approximations for these three parameters, the model could be more accurate if they were calculated from known atmospheric conditions.

The fourth limitation is the blank air filters have detectable concentrations of microcystins on them when they should be blank. The air filter spike analysis preliminary study was able to rule out contamination as a possible explanation, leaving the LC/MS/MS mistaking another compound for MC-LR as the next most likely explanation. The usage of double mass spectrometry should reduce the possibility of another compound being mistaken for MC-LR, but it still could be possible, given that the air filter blanks have MC-LR readings. While it is unknown if this is an issue or what the mistaken compound could be, it still does pose an issue that the MC-LR concentrations could potentially be lower than what the LC/MS/MS reports. Steps were taken to mitigate this issue, such as subtracting the average MC-LR concentration on the blank air filters from the field air filters, but this should be considered when analyzing samples, and future work should be done to determine the exact cause. This issue was not a deficiency in this study, but it could not be explained. A final challenge was the boat getting its thrusters stuck when hitting an underwater mat of algae. While it is easy to avoid heavily matted areas visible, it's much harder to avoid them when they are underwater. A potential solution to this issue could be either to mount a camera on the bow underwater for an extra set of eyes or design an apparatus to prevent algae from getting caught in the thrusters.

CHAPTER 7

CONCLUSION

Cyanobacteria harmful algal blooms (cHABS) are a serious threat to the water quality of Utah Lake and those who use it. Algal blooms can cause intense deterioration of the water quality through shifts in the pH, eutrophication, stratification, water discoloration, and changes in water transparency. Cyanobacteria, particularly microcystins, contain toxins that can have a wide range of effects on humans, from abdominal pain and skin irritation to liver disease, liver failure, and death. Government agencies have established a methodology for collecting and analyzing cHAB water samples to determine if the water poses a threat, but the current methodology calls for human grab sampling, posing possible risks to those who collect the water samples through potential contact. In addition, the presence of cyanobacteria in the water at Utah Lake is well understood, but the possible presence and effects of cyanobacteria in the air are not. While aerosolized cHABs have been measured in other locations, no studies have assessed cyanotoxins in aerosols surrounding Utah Lake. Further, there is no official methodology for collecting and analyzing aerosolized cHABs, nor are the potential public health risks understood, so agencies typically do not test for them. This study aimed to establish a methodology for collecting and analyzing aerosolized cHAB samples at Utah Lake, in addition to developing and deploying an unoccupied vehicle (UV) paired with a water sampler to collect cHAB water samples, reducing the need for human grab samples. Additionally, this work is of interest to individuals who want to automate water sample collection or remove direct human grab sampling, sample and analyze cHAB air samples, or conduct studies on the potential exposure of aerosolized cHABs.

The water samples at Lincoln Marina and Utah Lake State Park were both shown to have detectable concentrations of microcystins. Lincoln Marina overall had higher total microcystin concentrations in the water than Utah Lake State Park, with three of the samples all taken at the same grab sample site on the same day exceeding the UDEQ's total microcystin threshold of 8 µg/L; none of the samples at Utah Lake State Park exceeded the UDEQ's threshold. Congener MC-LR was the most dominant in the water and the primary driver of total microcystin concentrations at both campaign sites. Similarly, MC-LA was the less common congener with the lowest concentrations at both sites. The concentration and prevalence of the remaining five congeners differed between Lincoln Marina and Utah Lake State Park. The total microcystin concentration of the composite samples was in the lower range of sample concentrations for both Lincoln Marina and Utah Lake State Park. However, the composite samples were similar to at least one grab sample site at both campaign sites.

The air samples at Lincoln Marina and Utah Lake State Park were both shown to have detectable concentrations of microcystins, showing that the developed collection and analysis methodology for aerosolized microcystins was valid. Utah Lake State Park overall had higher total microcystin concentrations in the air than Lincoln Marina and had more air samples detect microcystins, with Utah Lake State Park having nine of nine samples detect microcystins while Lincoln Marina only had five of nine samples detect microcystins. Local water microcystin concentrations were shown to not be as important of a factor for microcystin aerosolization, as the microcystin concentrations in the water at Lincoln Marina were greater than the water concentrations at Utah Lake State Park, but the microcystin concentrations in the air at Utah Lake State Park were greater than air

concentrations at Lincoln Marina; this is further reinforced by the air-to-water ratio of Lincoln Marina being 10^{-8} to 10^{-9} , while the ratio for Utah Lake State Park was 10^{-6} to 10^{-7} . Wind speed, particularly high wind speed events, was shown to be a major driver of microcystin aerosolization, as Utah Lake State Park has the most intense wind with higher microcystin air concentrations. Congeners MC-LR, MC-YR, and MC-LA were found at both campaign sites, while MC-LW was only found in one sample at Utah Lake State Park; MC-RR, MC-LY, and MC-LF were not found in any samples at either campaign site. Flux footprints at both sites showed that while distance of up to 150 meters at Lincoln Marina and 300 meters at Utah Lake State Park could influence the microcystin concentrations at the air samples, the 25-50 meters from the dominant wind direction was the area that had the greater influence on air concentrations.

7.1 Future Work

This study has laid the groundwork for future work regarding microcystin air and water concentrations at Utah Lake and determining microcystins in the water and air in general, which would support research on the health ramifications of aerosolized microcystins. This study showed that a UV can take cHAB water samples that are similar to some grab samples at Utah Lake, but further work comparing the efficiency of UV samples to traditional grab samples could help give agencies more evidence for replacing traditional sampling with UV technology. This could be done by taking traditional grab samples with the UV or taking both traditional and UV samples at the same location. This study showed that microcystins are in the air at Utah Lake, but additional work could be done to further show the spatiotemporal relationship between microcystin air and water concentrations and weather parameters. One way that this could be done is by calculating

the possible fetch/flux footprint/zone of influence (ZOI) before sampling at a site to determine the location that will have the greatest influence on the air samples and then take water samples from there. Staying with the flux footprints, more detailed metrological and atmospheric data should be recorded in future runs so that the boundary layer height, Monin-Obukhov length, and friction velocity flux footprint prediction (FFP) model parameters will not have to be approximated, providing a more accurate footprint. Given a flux footprint, it would also be interesting in a future run to back-calculate the emission strength of the microcystins from the water to the air.

Season-long studies could also be conducted to show how microcystin air concentrations change throughout the bloom season and if certain times or conditions are worse than others. Given the apparent correlation between water recreation or boat paths with the aerosolization of microcystins, a log of the number of boats to come in and out of the marinas would be an interesting addition to see how influential boats are for microcystin aerosolization. It would be in the best interest of future researchers to also determine why the filter blanks are overestimating MC-LR. This study could not explain the overestimation but was able to account for it by subtracting the blank filters from the field filters. Being able to minimize or explain the background peaks misidentified as MC-LR would be crucial for future studies. In addition to further testing of microcystin air concentrations at Utah Lake, more research should be done on the toxicity and health effects of aerosolized microcystins. That includes how toxic microcystins in air are relative to microcystins in water, whether there are any differences between the health effects on humans and animals of microcystins in air vs. microcystins in water, and what the maximum daily inhaled concentration (MDIC) for aerosolized microcystins. Having

dedicated weather stations collocated with each air sampler could be beneficial in future studies, as while the MesoWest weather station used (Provo Airport) was close to Utah Lake State Park, it was farther away from Lincoln Marina and could be less representative of local site conditions.

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APPENDICES

APPENDIX A

LC/MS/MS PARAMETERS

Table A1

LC conditions for the analysis of microcystins

Time	A	B	Flow ml/min	Pressure
1.0 min	95%	5%	0.3 ml/min	600 bar
14.5 min	20%	80%	0.3 ml/min	600 bar
14.6 min	10%	90%	0.3 ml/min	600 bar
18.5 min	10%	90%	0.3 ml/min	600 bar
19.0 min	90%	10%	0.3 ml/min	600 bar

Note. Solvent A: 20 mM ammonium formate in water. Solvent B: acetonitrile.

Phenomenex Kinetex C8 2.6 µm, 2.1 x 100 mm, 5 µl injection.

Table A2

MSMS conditions for the analysis of microcystins

Compound	Precursor ion m/z	Product ion m/z	Fragmentation energy (V)	Collision energy (V)	Cell Acc	Retention Time min
MC-LA	910.5	134.9	380	60	4	9.75
MC-LF	987	134.9	380	68	4	10.7
MC-LR	995.5	134.9	380	60	4	8.9
MC-LW	1025.5	134.9	380	66	4	10.86
MC-LY	1002.5	134.9	380	72	4	10.05
MC-RR	519.9	134.9	380	44	4	8.58
MC-YR	523.3	134.9	380	32	4	8.78
Nodularin	825.4	134.9	380	64	4	8.15
MC-LR-d ₅ (extraction standard)	1028.6	134.9	380	72	4	10.68
Cyclosporin A, ¹³ C ₂ , d ₄ (internal standard)	1208.9	99.9	380	62	4	17.1

Note. Agilent Infinity 1290 liquid chromatograph (LC) interfaced with an Agilent 6490 triple quadrupole mass spectrometer/mass spectrometer (MS/MS).

APPENDIX B

PRELIMINARY STUDY SAMPLE CONCENTRATIONS

Table B1

Total microcystin concentrations and microcystin congener concentrations for water samples for the Lincoln Marina preliminary study from October 5th to October 6th, 2023

Sample	MC-RR (µg/L)	MC-YR (µg/L)	MC-LR (µg/L)	MC-LA (µg/L)	MC-LY (µg/L)	MC-LW (µg/L)	MC-LF (µg/L)	MC-Total (µg/L)
10/5 Morning 1	0.026	0.111	0.087	0.064	0.190	0.205	0.383	1.07
10/5 Morning 2	0.070	0.273	0.087	0.069	0.154	0.169	0.304	1.14
10/5 Morning 3	0.039	0.135	0.077	0.086	0.134	0.130	0.278	0.879
10/5 Midday 1	0.206	0.014	0.844	0.004	0.041	0.047	0.076	1.23
10/5 Midday 2	0.278	0.031	0.663	0.021	0.029	0.024	0.061	1.11
10/5 Midday 3	0.016	0.072	0.060	0.057	0.121	0.146	0.251	0.725
10/5 Evening 1	0.225	0.035	0.052	0.032	0.126	0.018	0.227	0.714
10/5 Evening 2	0.035	0.107	0.107	0.047	0.246	0.010	0.529	1.08
10/5 Evening 3	0.280	0.034	0.802	0.098	0.033	0.015	0.044	1.31
10/6 Morning 1	1.85	0.176	2.10	0.078	0.071	0.056	0.155	4.49
10/6 Morning 2	0.152	0.037	7.22	0.059	0.480	0.499	0.926	9.37
10/6 Morning 3	0.012	1.08	0.043	0.450	0.878	0.024	1.09	3.58
10/6 Midday 1	0.122	0.913	0.199	0.019	0.872	0.011	0.014	2.15
10/6 Midday 2	0.150	0.742	0.139	0.274	0.255	0.081	0.463	3.42
10/6 Midday 3	0.553	1.47	0.245	0.469	0.210	0.018	0.463	3.42

Sample	MC-RR ($\mu\text{g/L}$)	MC-YR ($\mu\text{g/L}$)	MC-LR ($\mu\text{g/L}$)	MC-LA ($\mu\text{g/L}$)	MC-LY ($\mu\text{g/L}$)	MC-LW ($\mu\text{g/L}$)	MC-LF ($\mu\text{g/L}$)	MC-Total ($\mu\text{g/L}$)
10/6 Evening 1	0.351	0.021	0.023	0.092	0.045	0.035	0.090	0.657
10/6 Evening 2	0.027	0.170	0.045	0.173	0.258	0.041	0.451	1.17
10/6 Evening 3	0.256	0.011	0.011	0.040	0.043	0.008	0.090	0.459

Table B2

Total microcystin concentrations and microcystin congener concentrations for air samples for the Lincoln Marina preliminary study from October 5th to October 6th, 2023

Sample	MC-RR (µg/L)	MC-YR (µg/L)	MC-LR (µg/L)	MC-LA (µg/L)	MC-LY (µg/L)	MC-LW (µg/L)	MC-LF (µg/L)	Total MC (µg/L)
HV-1	<0.1	<0.2	0.245	<0.1	<0.1	<0.1	<0.1	0.000
HV-2 (Blank)	<0.1	<0.2	0.341	<0.1	<0.1	<0.1	<0.1	0.341
HV-3 (Blank)	<0.1	<0.2	0.408	<0.1	<0.1	<0.1	<0.1	0.408
HV-4 (Blank)	<0.1	<0.2	0.322	<0.1	<0.1	<0.1	<0.1	0.322
8836 (Vol 7939)	<0.1	<0.2	0.419	<0.1	<0.1	<0.1	<0.1	0.000
8837 (Vol 7938)	<0.1	<0.2	0.420	<0.1	<0.1	<0.1	<0.1	0.000
8838 (Blank)	<0.1	<0.2	0.382	<0.1	<0.1	<0.1	<0.1	0.382
8839 (Blank)	<0.1	<0.2	0.389	<0.1	<0.1	<0.1	<0.1	0.389
8840 (Blank)	<0.1	<0.2	0.360	<0.1	<0.1	<0.1	<0.1	0.360

Note. Hi-Vol Average Blank MC-LR Concentration: 0.357 µg/L. Mini-Vol Average Blank MC-LR Concentration: 0.377 µg/L

APPENDIX C

LINCOLN MARINA SAMPLE CONCENTRATIONS

Table C1

Total microcystin concentrations and microcystin congener concentrations for water samples for Lincoln Marina from July 7th, 2024, to July 11th, 2024

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
LM-0708-GB11	0.011	0.008	0.974	0.003	0.009	0.027	0.022	1.05
LM-0708-GB12	0.016	0.023	2.34	0.003	0.014	0.041	0.035	2.47
LM-0708-GB13	0.018	0.002	1.84	0.007	0.002	0.047	0.031	1.96
LM-0708-GB21	0.131	0.009	29.6	0.007	0.079	0.240	0.164	30.3
LM-0708-GB22	0.142	0.016	26.5	0.004	0.067	0.229	0.163	27.1
LM-0708-GB23	0.101	0.014	10.4	0.007	0.050	0.149	0.108	10.8
LM-0708-GB31	0.006	0.009	0.190	0.003	0.003	0.006	0.009	0.228
LM-0708-GB32	0.004	0.018	0.132	0.001	0.003	0.006	0.007	0.171
LM-0708-GB33	0.005	0.008	0.123	0.002	0.003	0.007	0.007	0.155
LM-0708-C1	0.006	0.011	0.084	0.002	0.003	0.007	0.006	0.118

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
LM-0708-C2	0.005	0.015	0.069	<0.001	0.003	0.008	0.003	0.103
LM-0708-C3	0.006	0.013	0.087	0.001	0.003	0.005	0.007	0.123
LM-0709-GB11	0.020	0.005	1.15	0.002	0.027	0.100	0.065	1.37
LM-0709-GB12	0.017	0.014	1.43	0.002	0.031	0.110	0.073	1.68
LM-0709-GB13	0.019	0.013	1.18	0.004	0.026	0.073	0.057	1.37
LM-0709-GB21	0.023	0.005	1.27	0.002	0.005	0.024	0.017	1.35
LM-0709-GB22	0.113	0.033	2.44	0.003	0.038	0.138	0.080	2.84
LM-0709-GB23	0.043	0.013	2.44	0.002	0.018	0.070	0.037	2.62
LM-0709-GB31	0.004	0.019	0.183	<0.001	0.001	0.004	0.002	0.214
LM-0709-GB32	0.003	0.010	0.185	<0.001	0.004	0.005	0.003	0.211
LM-0709-GB33	0.005	0.006	0.199	<0.001	0.003	0.005	0.002	0.221
LM-0709-C1	0.005	0.015	0.088	0.002	0.003	0.005	0.005	0.123
LM-0709-C2	0.004	0.009	0.091	<0.001	0.002	0.005	0.005	0.117
LM-0709-C3	0.004	0.009	0.084	0.001	0.002	0.007	0.005	0.113

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
LM-0710-GB11	0.037	0.020	1.22	0.004	0.018	0.045	0.036	1.38
LM-0710-GB12	0.046	0.010	0.980	0.002	0.016	0.053	0.034	1.14
LM-0710-GB13	0.022	0.014	1.07	<0.001	0.011	0.029	0.024	1.17
LM-0710-GB21	0.013	0.010	0.410	0.002	0.007	0.018	0.014	0.475
LM-0710-GB22	0.033	0.012	0.372	<0.001	0.007	0.013	0.017	0.454
LM-0710-GB23	0.011	0.003	0.122	<0.001	0.004	0.012	0.008	0.159
LM-0710-GB31	0.003	0.010	0.094	<0.001	0.005	0.009	0.007	0.128
LM-0710-GB32	0.008	0.003	0.108	0.002	0.003	0.012	0.009	0.145
LM-0710-GB33	0.008	0.019	0.202	0.003	0.008	0.022	0.011	0.273
LM-0710-C1	0.008	0.009	0.120	<0.001	0.004	0.009	0.011	0.160
LM-0710-C2	0.135	0.175	0.064	0.009	0.059	0.160	0.137	2.00
LM-0710-C3	0.012	0.013	0.128	<0.001	0.004	0.017	0.012	0.186
LM-0711-GB11	0.012	0.014	0.194	<0.001	0.009	0.018	0.016	0.264
LM-0711-GB12	0.006	0.013	0.202	<0.001	0.007	0.018	0.021	0.267

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
LM-0711-GB13	0.014	0.011	0.152	<0.001	0.005	0.017	0.012	0.210
LM-0711-GB21	0.078	0.012	1.66	0.002	0.054	0.133	0.119	2.06
LM-0711-GB22	0.024	0.005	0.488	0.002	0.012	0.037	0.032	0.600
LM-0711-GB23	0.015	0.014	0.433	0.002	0.013	0.033	0.024	0.534
LM-0711-GB31	0.004	0.003	0.086	0.002	0.003	0.010	0.005	0.114
LM-0711-GB32	0.005	0.010	0.079	0.003	0.003	0.006	0.004	0.109
LM-0711-GB33	0.003	0.005	0.066	<0.001	0.003	0.007	0.004	0.088
LM-0711-C1	0.006	0.008	0.091	0.001	0.004	0.011	0.008	0.129
LM-0711-C2	0.007	0.006	0.156	<0.001	0.007	0.015	0.014	0.205
LM-0711-C3	0.007	0.007	0.144	<0.001	0.009	0.010	0.011	0.188
Trip Blank 1	<0.001	0.007	0.016	<0.001	<0.001	<0.001	0.001	0.024
Trip Blank 2	<0.001	0.004	0.004	<0.001	<0.001	<0.001	0.001	0.009
Trip Blank 3	<0.001	0.005	0.011	<0.001	<0.001	<0.001	0.002	0.017

Table C2

Total microcystin concentrations and microcystin congener concentrations for air samples for Lincoln Marina from July 7th, 2024, to July 11th, 2024

Sample	MC-RR (pg/m ³)	MC-YR (pg/m ³)	MC-LR (pg/m ³)	MC-LA (pg/m ³)	MC-LY (pg/m ³)	MC-LW (pg/m ³)	MC-LF (pg/m ³)	MC-Total (pg/m ³)
Air 1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	0.000
Air 2	<0.1	19.9	<0.1	<0.1	<0.1	<0.1	<0.1	19.9
Air 3	<0.1	<0.2	22.5	8.21	<0.1	<0.1	<0.1	30.7
Air 4	<0.1	<0.2	10.4	<0.1	<0.1	<0.1	<0.1	10.4
Air 5	<0.1	<0.2	13.8	7.49	<0.1	<0.1	<0.1	21.3
Air 6	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	0.000
Air 7	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	0.000
Air 8	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	0.000
Air 9	<0.1	16.0	4.56	<0.1	<0.1	<0.1	<0.1	20.6

Note. Average Blank MC-LR Concentration: 0.269 µg/L.

APPENDIX D

UTAH LAKE STATE PARK SAMPLE CONCENTRATIONS

Table D1

Total microcystin concentrations and microcystin congener concentrations for water samples for Utah Lake State Park from August 12th, 2024, to August 15th, 2024

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
ULSP-0812-GB11	0.009	0.002	0.006	<0.001	<0.001	<0.001	0.001	0.018
ULSP-0812-GB12	0.007	0.007	0.017	<0.001	<0.001	0.002	0.002	0.033
ULSP-0812-GB13	0.008	0.007	0.010	<0.001	<0.001	0.001	0.002	0.029
ULSP-0812-GB21	0.003	0.015	0.009	0.001	<0.001	<0.001	<0.001	0.029
ULSP-0812-GB22	0.002	0.012	0.017	0.001	0.002	0.002	0.002	0.038
ULSP-0812-GB23	0.002	0.026	0.014	<0.001	<0.001	0.004	<0.001	0.046
ULSP-0812-GB31	0.004	0.002	0.011	0.002	<0.001	<0.001	<0.001	0.019
ULSP-0812-GB32	0.002	<0.002	0.008	<0.001	0.001	<0.001	<0.001	0.011
ULSP-0812-GB33	0.003	<0.002	0.008	<0.001	<0.001	<0.001	0.002	0.013
ULSP-0812-C1	0.002	0.010	0.006	<0.001	<0.001	<0.001	<0.001	0.017

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
ULSP-0812-C2	0.003	0.013	0.011	<0.001	<0.001	<0.001	<0.001	0.027
ULSP-0812-C3	0.003	0.014	0.005	<0.001	<0.001	<0.001	<0.001	0.022
ULSP-0813-GB11	0.006	<0.002	0.013	0.001	0.001	<0.001	<0.001	0.022
ULSP-0813-GB12	0.004	0.007	0.011	0.001	<0.001	0.002	0.000	0.025
ULSP-0813-GB13	0.005	0.010	0.015	0.001	<0.001	<0.001	<0.001	0.032
ULSP-0813-GB21	0.001	0.008	0.008	<0.001	<0.001	<0.001	<0.001	0.017
ULSP-0813-GB22	0.002	0.013	0.009	<0.001	<0.001	<0.001	0.002	0.025
ULSP-0813-GB23	0.002	0.007	0.008	0.002	<0.001	<0.001	0.001	0.020
ULSP-0813-GB31	0.002	<0.002	0.012	0.001	<0.001	<0.001	<0.001	0.015
ULSP-0813-GB32	0.004	<0.002	0.013	0.001	<0.001	0.001	0.001	0.021
ULSP-0813-GB33	0.003	0.011	0.010	0.002	<0.001	<0.001	<0.001	0.025
ULSP-0813-C1	0.003	0.008	0.009	0.001	<0.001	<0.001	<0.001	0.021
ULSP-0813-C2	0.003	0.011	0.012	<0.001	<0.001	<0.001	<0.001	0.026
ULSP-0813-C3	0.002	0.003	0.008	<0.001	<0.001	<0.001	0.001	0.014

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
ULSP-0814-GB11	0.008	0.002	0.010	0.003	<0.001	0.001	0.002	0.027
ULSP-0814-GB12	0.004	0.006	0.015	<0.001	0.001	<0.001	<0.001	0.026
ULSP-0814-GB13	0.006	0.005	0.015	0.002	<0.001	0.001	0.002	0.030
ULSP-0814-GB21	0.004	0.020	0.011	<0.001	<0.001	0.001	<0.001	0.036
ULSP-0814-GB22	0.005	0.025	0.011	0.001	<0.001	<0.001	0.002	0.045
ULSP-0814-GB23	0.003	0.006	0.012	<0.001	0.001	<0.001	<0.001	0.023
ULSP-0814-GB31	0.006	<0.002	0.018	<0.001	<0.001	<0.001	0.002	0.026
ULSP-0814-GB32	0.006	<0.002	0.014	<0.001	0.002	0.002	0.002	0.025
ULSP-0814-GB33	0.004	0.003	0.013	<0.001	<0.001	<0.001	<0.001	0.021
ULSP-0814-C1	0.002	0.008	0.009	<0.001	<0.001	<0.001	0.002	0.020
ULSP-0814-C2	0.001	0.013	0.009	0.001	<0.001	<0.001	<0.001	0.025
ULSP-0814-C3	0.002	0.020	0.007	0.001	<0.001	<0.001	<0.001	0.030
ULSP-0815-GB11	0.018	0.037	0.081	<0.001	<0.001	0.003	0.002	0.141
ULSP-0815-GB12	0.006	<0.002	0.024	<0.001	<0.001	<0.001	<0.001	0.029

Sample	MC-RR (ug/L)	MC-YR (ug/L)	MC-LR (ug/L)	MC-LA (ug/L)	MC-LY (ug/L)	MC-LW (ug/L)	MC-LF (ug/L)	Total MC (ug/L)
ULSP-0815-GB13	0.006	0.012	0.012	<0.001	<0.001	0.002	0.003	0.035
ULSP-0815-GB21	0.005	0.015	0.015	0.001	<0.001	0.002	<0.001	0.038
ULSP-0815-GB22	0.006	0.006	0.015	0.002	<0.001	<0.001	<0.001	0.029
ULSP-0815-GB23	0.002	0.005	0.012	<0.001	<0.001	0.001	<0.001	0.021
ULSP-0815-GB31	<0.001	0.008	0.007	<0.001	<0.001	0.001	<0.001	0.015
ULSP-0815-GB32	0.003	0.004	0.006	<0.001	<0.001	0.001	<0.001	0.014
ULSP-0815-GB33	0.004	<0.002	0.005	<0.001	<0.001	<0.001	0.002	0.011
ULSP-0815-C1	0.003	<0.002	0.007	<0.001	<0.001	<0.001	<0.001	0.011
ULSP-0815-C2	0.002	0.007	0.009	<0.001	<0.001	<0.001	0.002	0.021
ULSP-0815-C3	0.005	0.019	0.014	0.003	0.002	0.001	0.004	0.047
Trip Blank 1	<0.001	<0.002	0.001	<0.001	<0.001	<0.001	<0.001	0.001
Trip Blank 2	<0.001	<0.002	0.003	<0.001	<0.001	<0.001	<0.001	0.003
Trip Blank 3	<0.001	<0.002	0.001	<0.001	<0.001	<0.001	<0.001	0.001

Table D2

Total microcystin concentrations and microcystin congener concentrations for air samples for Utah Lake State Park from August 12th, 2024, to August 15th, 2024

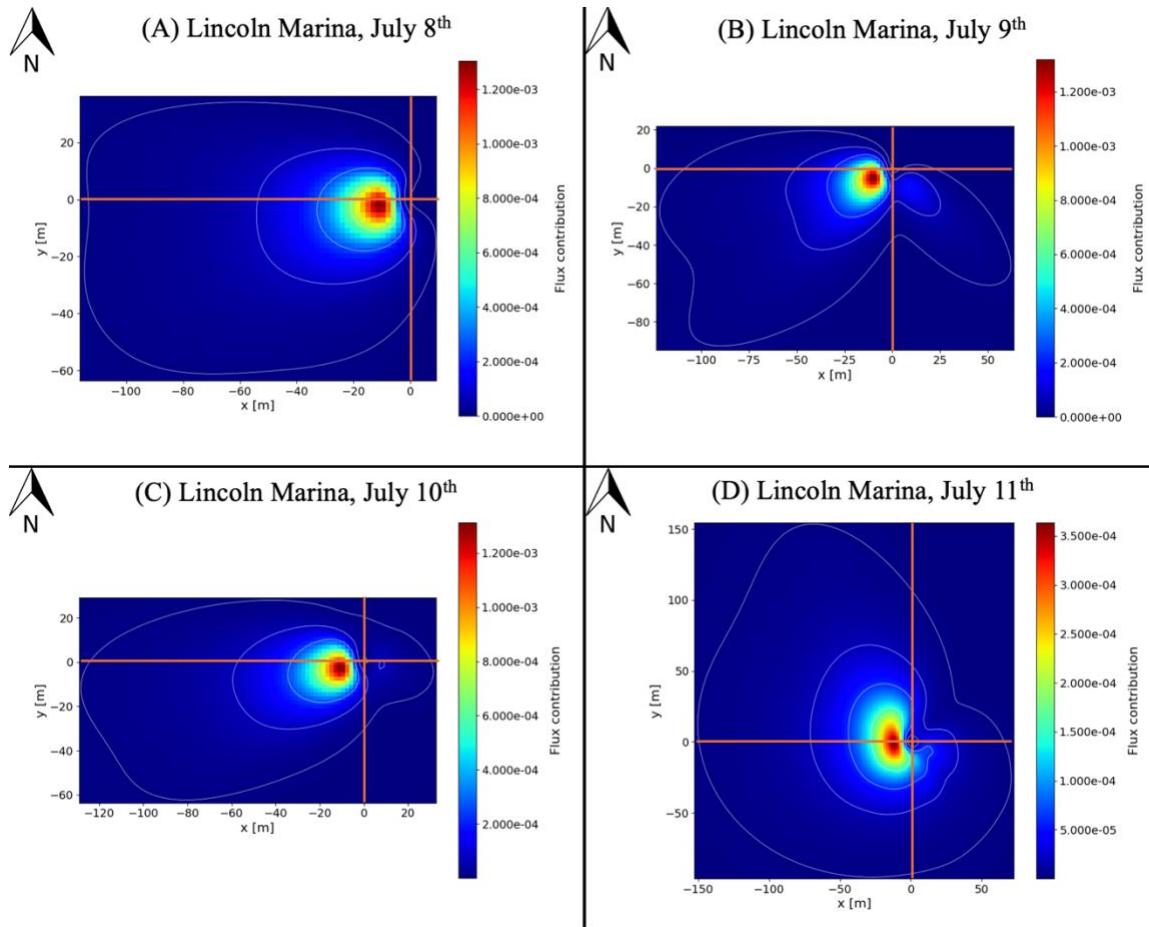
Sample	MC-RR (pg/m ³)	MC-YR (pg/m ³)	MC-LR (pg/m ³)	MC-LA (pg/m ³)	MC-LY (pg/m ³)	MC-LW (pg/m ³)	MC-LF (pg/m ³)	Total MC (pg/m ³)
Air 1	<0.1	<0.2	79.3	<0.1	<0.1	<0.1	<0.1	79.3
Air 2	<0.1	22.3	<0.1	<0.1	<0.1	<0.1	<0.1	22.3
Air 3	<0.1	<0.2	9.44	<0.1	<0.1	7.62	<0.1	17.1
Air 4	<0.1	17.0	<0.1	<0.1	<0.1	<0.1	<0.1	17.0
Air 5	<0.1	22.6	47.3	<0.1	<0.1	<0.1	<0.1	69.9
Air 6	<0.1	<0.2	37.2	<0.1	<0.1	<0.1	<0.1	37.2
Air 7	<0.1	<0.2	<0.1	11.2	<0.1	<0.1	<0.1	11.2
Air 8	<0.1	20.3	<0.1	<0.1	<0.1	<0.1	<0.1	20.3
Air 9	<0.1	<0.2	12.8	<0.1	<0.1	<0.1	<0.1	12.8

APPENDIX E

FETCH/FLUX FOOTPRINTS FOR SUMMER 2024 CAMPAIGN SITES

Figure E1

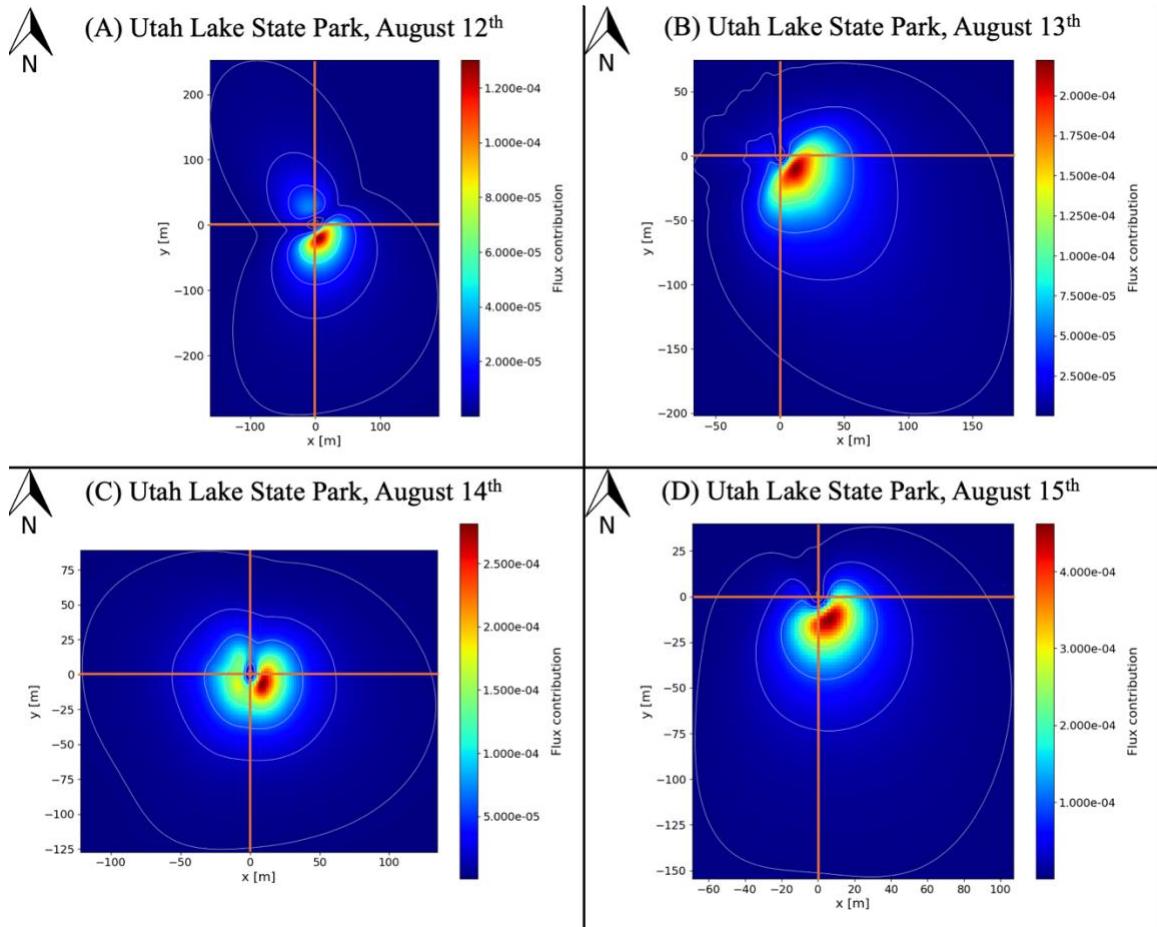
Flux footprint at Lincoln Marina on (A) July 8th, 2024. (B) July 9th, 2024. (C) July 10th, 2024. (D) July 11th, 2024



Note. For all flux footprints, the positive y direction assumes north, while the positive x direction assumes east. The intersection of the two orange lines shows the location of the sampler

Figure E2

Flux footprint at Utah Lake State Park on (A) August 12th, 2024. (B) August 13th. (C) August 14th, 2024. (D) August 15th, 2024



Note. For all flux footprints, the positive y direction assumes north, while the positive x direction assumes east. The intersection of the two orange lines shows the location of the sampler.