Utah Lake Water Quality Study—Strategic Research Plan

FINAL

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Version 4.3

PRESENTED TO

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Cover image: Aerial View of Provo Utah with River Valley and Utah Lake, by Aqua Mechanical. Source file available at https://www.flickr.com/photos/aquamech-utah/24776739750/in/photostream/

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ABBREVIATIONS

Abbreviation	Definition
DO	Dissolved Oxygen
DWQ	Division of Water Quality
EFDC	Environmental Fluid Dynamics Code
EPA	United States Environmental Protection Agency
HAB	Harmful Algal Bloom
N	Nitrogen
NNC	Numeric Nutrient Criteria
P	Phosphorus
RFP	Request for Proposal
SC	Steering Committee
SP	Science Panel
S-R	Stressor-Response
SRP	Strategic Research Plan
TMDL	Total Maximum Daily Loads
ULC	Utah Lake Commission
ULWQS	Utah Lake Water Quality Study
WQB	Water Quality Board
WASP	Water Quality Simulation Program

1.0 INTRODUCTION

1.1 OVERVIEW

In November 2015, Utah initiated the Utah Lake Water Quality Study (ULWQS) to address problems stemming from excessive concentrations of nutrients, which cause large seasonal algal blooms, elevated pH, and possible cyanotoxin production during harmful algal blooms. The goal of the ULWQS is to evaluate the effect of nutrient enrichment on Utah Lake's recreational, aquatic life, and agricultural designated uses and to develop site-specific numeric nutrient criteria (NNC) for nitrogen (N) and phosphorus (P) water quality criteria to protect these uses. The ULWQS has three phases. The first, which was completed in December 2018, involved data gathering and characterization. The second (which is currently underway) is to evaluate factors that affect beneficial use support and Harmful Algal Blooms in Utah Lake, guide additional research to address data gaps, and to develop NNC for P and N. The third phase will involve evaluating current use designations and the scientific and economic feasibility of achieving the recommended criteria.

The ULWQS is guided by a Stakeholder Process, which established a 16-member interest-based Steering Committee (SC) and a 10-member disciplinary-based Science Panel (SP). The SC is chaired jointly by the Utah Lake Commission (ULC) and Division of Water Quality (DWQ). It is charged with guiding water quality criteria development and recommending in-lake water quality criteria (including elements of magnitude, frequency, and duration) to the ULC and DWQ for adoption by the state Water Quality Board (WQB). The SC is supported by the SP, whose purpose is to guide water quality criteria development and to oversee targeted scientific studies. Figure 1 shows the various organizations involved in the ULWQS.

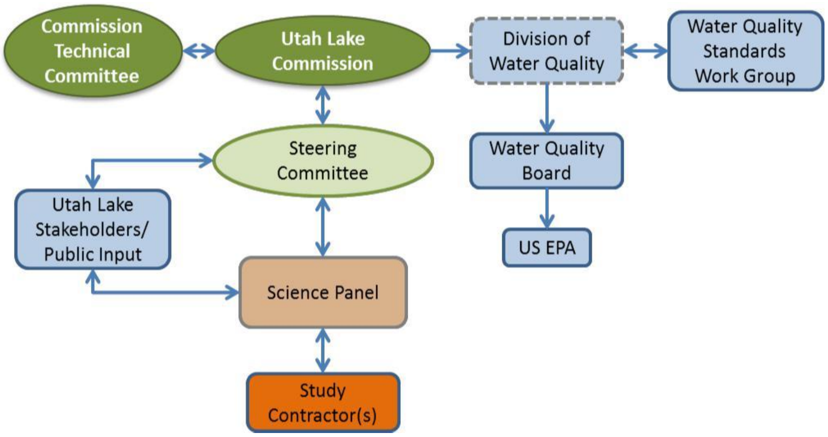


Figure 1. Flow diagram showing the various organizations involved in the ULWQS.

Phase 2 of the ULWQS is driven largely by the SC and SP. The SC has charged the SP with two main responsibilities (which are complementary but distinct). One is to respond to charge questions posed by the SC about historic, present, and future nutrient dynamics in Utah Lake (the charge questions are discussed in detail in Section 2). The SP's second responsibility is to develop and implement a framework to recommend NNC for Utah Lake that will protect its designated uses. The SP is currently working on the NNC framework, which will be based on multiple lines of evidence (stressor-response, reference-based and scientific literature). The SP's ability to answer the charge questions and develop scientifically defensible NNC is constrained by data gaps and uncertainty. While there is no way to completely eliminate these two factors from criteria development, the SP is taking steps to reduce them by identifying and addressing major knowledge gaps and developing uncertainty guidance, which will inform a strategic research planning process as well as exploratory research.

1.2 COMPONENTS OF THE ULWQS PROCESS

Figure 2 shows the relationship among the technical framework components in Phase 2 of the ULWQS, which include a literature review, development of conceptual models, data gaps analysis, NNC framework development, uncertainty guidance, strategic research planning and exploratory research. Some of these components have been completed, while others are ongoing. All are linked either directly or indirectly. The first step was to conduct a literature review, which was completed in March 2019 (Tetra Tech 2019a). It summarized various NNC development options for the SP to consider and formed the basis of the approaches proposed in the framework document (Tetra Tech 2019b). It also informed conceptual model development (Tetra Tech 2019c). The conceptual models synthesize critical management goals and assessment endpoints and measures that are the focus of NNC development. Another component was data characterization (Tetra Tech 2019d), which synthesized what data are available to quantify linkages in the conceptual model. The SP used the data characterization in combination with the conceptual models to identify data gaps. The data gap analysis and framework informed each other (the framework laid out the data requirements for various options and the data gap analysis helped inform which options were possible). Another component involved development of uncertainty guidance (Tetra Tech 2019e) to go along with the framework to help the SP identify, characterize, and communicate uncertainty. The final two components are a Strategic Research Plan (SRP) and exploratory research.

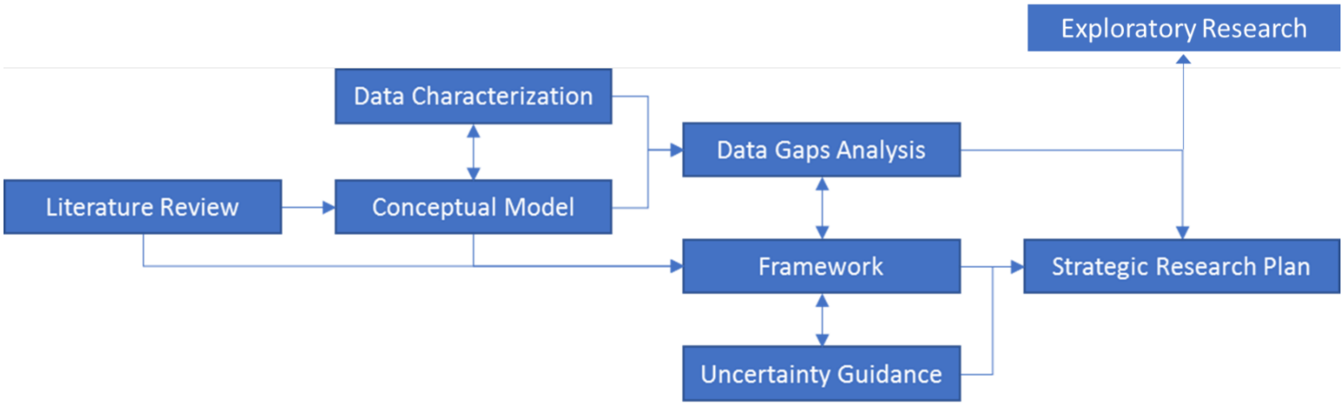


Figure 2. Relationship among technical framework components

The three main components that inform the SRP are the data gap analysis, framework and uncertainty guidance. The framework document (Tetra Tech 2019b) describes the approach that will be used to derive in-lake NNC for N and P. It informs the SRP by laying out the data requirements for setting NNC and identifying the knowledge gaps that constrain which approaches are possible. Table 1 summarizes the lines of evidence that the SP is planning to use. The primary lines of evidence will be based on stressor-response (S-R) relationships and the reference condition approach. The S-R approach will utilize mechanistic and empirical models. The mechanistic model can be used to generate N and P load targets that meet desired beneficial use conditions and can be translated into concentrations for assessment. The empirical models will relate stressors (e.g., N or P) to assessment endpoint measures such as changes in biological composition (ecosystem structure) or biogeochemical processes (ecosystem functions). For the reference-based approach, paleolimnological data from Utah Lake will be used to better understand historical conditions, and the mechanistic model will be used to run a natural condition scenario in which loads are set to minimal or no human contributions. Observed data from Utah Lake and selected state and regional datasets may be evaluated as additional reference-based lines of evidence. As a secondary line of evidence, literature will be reviewed to evaluate how the proposed NNC values for Utah Lake compare to values from other studies. The framework for setting NNC is discussed in greater detail in Section 3.

Table 1. Multiple lines of evidence will be used when deriving NNC for Utah Lake.

Type	Line of evidence	Planning to use
Stressor-Response	Mechanistic model	yes
	Empirical	yes
Reference-based	Direct observation (data collection)	potentially
	Paleolimnological reconstruction of past conditions	yes
	Model-based prediction or extrapolation of reference conditions	yes
Scientific Literature		yes

The uncertainty guidance (Tetra Tech 2019e) also informs the SRP. Uncertainty is inherent to any scientific study, and it is important to evaluate and communicate uncertainty to scientists, decision-makers, and the public in consistent, transparent, traceable, and understandable ways. The SP's ability to perform its tasks is constrained by data gaps and uncertainty. Although these factors can and will be reduced through additional research, they cannot be eliminated. The purpose of the uncertainty guidance is to describe the process that the SP will use to quantify and communicate the level of certainty in their findings and recommendations. The way in which uncertainty is evaluated will depend on the approach/line of evidence being used by the SP to set the NNC and includes both qualitative expressions of confidence as well as quantitative measures. For each line of evidence, uncertainty specifically associated with that line will be evaluated and communicated. The SP will then use their expert judgment to combine these various estimates of uncertainty into an overall evaluation of the uncertainty associated with any conclusion, including the protectiveness of proposed numeric values. That evaluation will incorporate the type, amount of and quality of evidence against the level of agreement (Figure 3). Through this process, the SP will be able to identify the areas that have the largest uncertainty, which will help inform their recommendations on what additional research to prioritize to improve their ability to answer the charge questions and develop scientifically defensible NNC.

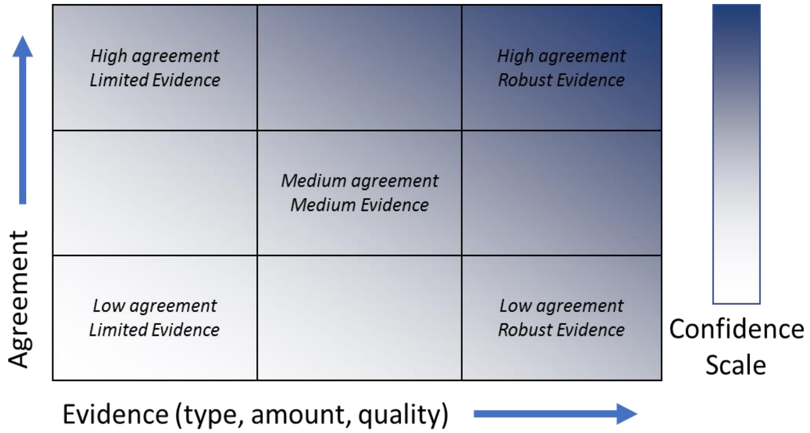


Figure 3. Matrix for guiding evaluation of the confidence in scientific conclusions based on the amount of and agreement among evidence

The data-gap analysis and summary of additional monitoring needs is the third main driver that informs the SRP. Identification of data gaps stems from the conceptual models (which establish the important pathways), data characterization and analysis (which identify the sufficiency of data to assess these important pathways) and by matching the SP's charge questions and NNC process against what has been or is being quantified. The data gaps are also informed by the NNC framework (Tetra Tech 2019b), which lays out the data requirements for options for deriving NNC. The data gaps analysis in turn helps inform which options for setting NNC are possible. Results from the data gaps analysis are not being written up in a standalone document but instead are being integrated into this document, where they will be used to help inform future strategic research planning to fill knowledge gaps.

1.3 ONGOING RESEARCH

Exploratory research is one of the components in the technical framework that links to the SRP and data gap analysis (Figure 2). This component addresses knowledge gaps about nutrient dynamics in Utah Lake that the SP feels they can address through targeted studies that will improve their ability to answer the charge questions and derive scientifically defensible NNC. Over the past year, DWQ has funded three initial projects to address immediate, known knowledge gaps. They include: a paleolimnological (paleo) study; bioassays to learn more about which nutrients are limiting, and whether there are seasonal and spatial dynamics in nutrient limitation; and a study to examine sediment–water-nutrient interactions.

The paleo study will help the SP understand the historical (pre-settlement) trophic state and nutrient regime of Utah Lake and how it has changed over time, which is important for NNC development and for understanding appropriate targets for protection or restoration. Results will allow the SP to understand, with greater certainty, historic conditions for: nutrient and relevant elemental conditions (including analysis of relative availability of bound fractions) to include, at a minimum, iron, calcium and aluminum; isotopic ^{15}N and ^{13}C conditions, and others as deemed appropriate; water clarity conditions; macrophyte presence, extent and quantity; diatom assemblage composition; trophic state; and, to the extent possible, inferred pH and thermal environmental conditions. The study is expected to be completed by January 31, 2021.

The bioassay study will help address knowledge gaps on spatial and temporal nutrient limitation dynamics in Utah Lake. To learn more about seasonal dynamics, experiments will be conducted during three time periods (mid-summer (2019), early fall (2019), and spring bloom (2020)). Spatial dynamics will be examined by collecting data from three locations that capture a range of trophic state and nutrient delivery: Provo Bay; main body of lake-east; and main body of lake, west. There will be four treatments (control, N, P, N+P), with three replicates each. Results are expected to be available by December 31, 2020.

The third study will provide information on sediment–water-nutrient interactions in Utah Lake. It will include calculations and results of sediment equilibrium P concentrations under oxic conditions, anoxic conditions, and a pH gradient. It will also include estimates of sediment oxygen demand, as well as information on the role of sediment resuspension on nutrient releases or removal, primarily via calcite scavenging. The experiments were performed on cores collected from two sites —one site in Provo Bay and one site from the main body of the lake at an established DWQ monitoring site. Thirty-nine sediment cores will be collected from each site, for a total of 78 cores. Results and a final report were available May 29, 2020.

1.4 DOCUMENT PURPOSE

The purpose of this document is to: 1) identify major remaining knowledge and data gaps that are constraining the certainty and confidence with which the SP can respond to charge questions and recommend NNC; and 2) to recommend strategic research to fill those knowledge and data gaps. Section 2 contains a review of the SP's charge questions and a summary of which are/are not being addressed by data analysis efforts and the ongoing research efforts. Section 3 discusses the data requirements for deriving NNC and identifies the biggest information needs for improving the SP's ability to develop scientifically defensible NNC. Section 4 concludes with a strategic research plan (SRP) in which the SP recommends and prioritizes studies to address the major remaining knowledge gaps that are constraining their ability to answer the charge questions and derive NNC.

2.0 INFORMATION NEEDS FOR CHARGE QUESTIONS

2.1 KNOWLEDGE GAPS RELATED TO CHARGE QUESTIONS

The SP was tasked with answering 26 charge questions, which can be distilled down into three overarching 'high-level' questions:

1. What was the historic ecological and nutrient condition of Utah Lake pre-settlement and how has it changed?
2. What is the current ecological and nutrient condition?
3. What additional information is needed?
4. Can the lake be improved given current management constraints?

Each of the three high-level charge questions have subsets of questions, some of which are currently being addressed through the data characterization/analysis component of the framework or through the ongoing research projects that were briefly described in Section 1.3. Table 2 lists the four questions that fall under Charge Question #1 (historical condition) and shows which ones are/are not being addressed. Two of the questions (1.2 and 1.4) will be fully addressed by the paleo study. These pertain to the historic P, N, and silicon concentrations (1.2) and the historical water quality, trophic state, and nutrient regime of the lake as determined from photopigments and DNA. Question 1.1 (historical trophic state and nutrient regime based on diatom and macrophyte community) will be partially addressed by the paleo study and data analyses. The part of Question 1.1 that is not being addressed pertains to the environmental requirements for diatoms and extant macrophyte species. Question 1.3 (population trajectory/growth of carp over time and how this relates to the trophic state and nutrient regime) is not being addressed at this time (Table 2).

Table 2. Question #1 (historical condition) is divided into four subsets of questions (some of which have additional sub-questions). Questions that are not currently being addressed are highlighted in yellow.

Questions	Being addressed
1.1. What does the diatom community and macrophyte community in the paleo record tell us about the historical trophic state and nutrient regime of the lake?	
i. Can diatom (benthic and planktonic) and/or macrophyte extent or presence be detected in sediment cores? And if so, what are they?	Paleo RFP
ii. What were the environmental requirements for diatoms and extant macrophyte species?	Data analysis
iii. How have environmental conditions changed over time?	Data analysis
1.2. What were the historic phosphorus, nitrogen, and silicon concentrations as depicted by sediment cores? (add calcium, iron, and potentially N and P isotopes)	Paleo RFP
1.3. What information do paleo records (eDNA/scales) provide on the population trajectory/growth of carp over time? What information do the paleo records provide on the historical relationship between carp and the trophic state and nutrient regime of the lake?	Contemporary data gathered by carp monitoring program
1.4. What do photopigments and DNA in the paleo record tell us about the historical water quality, trophic state, and nutrient regime of the lake?	Paleo RFP

Charge Question #2 (current conditions) has five subsets of questions, which are listed in Table 3. One question (2.3, which explores linkages between changes in nutrient regime and Harmful Algal Blooms (HABs)), will be fully addressed by the sediment and bioassay projects and the data analyses. Another question (2.5, which considers nutrient-related impacts to warm water aquatic life, waterfowl, shorebirds, and water-oriented wildlife), is not being addressed at this time. The other three questions (2.1, 2.2 and 2.4) are being partially addressed by data analyses and the ongoing sediment project (Section 1.3). Question 2.1 explores impacts of carp on the biology/ecology and nutrient cycling in the lake. The parts of Question 2.1 that are not being addressed pertain to bioturbation, the effect of carp removal on macrophytes, nutrients, secchi depth, turbidity, and primary productivity, and the effects of wind action versus carp foraging on non-algal turbidity/sediment resuspension. Question 2.2 is about the environmental requirements for submerged macrophytes that are currently present at Utah Lake. Its sub-questions about the role of lake elevation and drawdown in macrophyte recovery and the resiliency of different macrophyte species to drawdowns and nutrient related impacts are not being addressed at this time. The last question (2.4, which explores how sediments affect nutrient cycling in Utah Lake), has two sub-questions that will require further research: the effect of reducing sediment inputs on nutrient concentrations in the water column (and lag time for recovery); and the interaction of lake stratification (and weather patterns) on anoxia and phosphorus release into the water column.

Table 3. Question #2 (current conditions) is divided into five subsets of questions (some of which have additional sub-questions). Questions that are not currently being addressed are highlighted in yellow.

Questions		Being addressed
2.1. What are the impacts of carp on the biology/ecology and nutrient cycling of the lake and how are those impacts changing with ongoing carp removal efforts?		
	i. What contribution do carp make to the total nutrient budget of the lake via excretion rates and bioturbation? How much nutrient cycling can be attributed to carp?	Data analysis covers all but bioturbation
	ii. What is the effect of carp removal efforts on macrophytes, nutrients, secchi depth, turbidity, and primary productivity?	Proposed future work in sections 4.2.12-4.2.14
	iii. How much non-algal turbidity and nutrient cycling is due to wind action versus carp foraging? How much does sediment resuspension contribute to light limitation, and does wind resuspension contribute substantially in the absence of carp?	Partially by data analysis and EFDC model as to wind action; some literature for carp.
2.2 What are the environmental requirements for submerged macrophytes currently present at Utah Lake?		
	i. What is the role of lake elevation and drawdown in macrophyte recovery? Are certain species more resilient to drawdowns and nutrient related impacts? Can some species establish/adapt more quickly?	Partially by Landom et al. (2019)
	ii. What is the relationship between carp, wind, and macrophytes on non-algal turbidity and nutrient cycling in the lake? What impact could macrophyte reestablishment have?	Data analysis
2.3. What are the linkages between changes in nutrient regime and Harmful Algal Blooms (HABs)?		
	i. Where do HABs most frequently start/occur? Are there hotspots and do they tend to occur near major nutrient sources? Data analysis	Data analysis
	ii. Which nutrients are controlling primary production and HABs and when?	Bioassay RFP
	iii. If there are linkages between changes in nutrient regime and HABs, what role if any does lake elevation changes play?	Data analysis
	iv. How do other factors affect HAB formation in Utah Lake (e.g., climate change; temperature; lake stratification; changes in zooplankton and benthic grazers and transparency)	Data analysis
	v. What is the role of calcite "scavenging" in the phosphorus cycle?	Sediment RFP

	vi. What is the relationship between light extinction and other factors (e.g., algae, TSS, turbidity)?	Data analysis
2.4. How do sediments affect nutrient cycling in Utah Lake?		
	i. What are current sediment equilibrium P concentrations (EPC) throughout the lake? What effect will reducing inputs have on water column concentrations? If so, what is the expected lag time for lake recovery after nutrient inputs have been reduced?	Partially with the Sediment RFP, proposed future work in section 4.2.3
	ii. What is the sediment oxygen demand of, and nutrient releases from, sediments in Utah Lake under current conditions?	Sediment RFP
	iii. Does lake stratification [weather patterns] play a result in anoxia and phosphorus release into the water column? Can this be tied to HAB formation?	Partially by data analysis
2.5. For warm water aquatic life, waterfowl, shorebirds, and water-oriented wildlife:		
	i. Where and when in Utah Lake are early life stages of fish present?	No
	ii. Which species are most sensitive and need protection from nutrient-related impacts?	No

The third high-level charge question asks what additional information is needed for setting NNC that supports Utah Lake's beneficial uses. Question 3 has three components (none of which are being addressed at this time): warm water aquatic life, waterfowl, shorebirds, and water-oriented wildlife; primary contact recreation; and agricultural uses including irrigation of crops and stock watering. There is also a fourth question that will be addressed later, after the studies on the three high-level questions are underway. Question 4 explores whether an improved stable state can be reached under the constraints of current water and fishery management. It has three components -

- 4.1 What would be the current nutrient regime of Utah Lake assuming no nutrient inputs from human sources?
- 4.2 Assuming current water management, would nutrient reductions support a shift to a macrophyte-dominated state within reasonable planning horizons (i.e., 30- 50 years)?
- 4.3 If the lake stays in a phytoplankton-dominated state, to what extent can the magnitude, frequency, and extent of harmful and nuisance algal blooms be reduced through nutrient reductions?

The answers to the three high-level questions will be used to inform the scope of Question #4. The Science Panel intends to answer Question 4 before finalizing the NNC.

2.2 SUMMARY OF REMAINING MAJOR KNOWLEDGE/DATA GAPS

Identifying and addressing knowledge gaps will be an iterative, ongoing process with the ULWQS. Below is a summary of the charge questions that, at this time, do not have ongoing efforts aimed at addressing them, and which, therefore, could benefit from additional research to reduce uncertainty:

- What effect does carp removal have on macrophytes, nutrients, clarity, and primary productivity?
- What is the effect of lake elevation on macrophyte recovery? Are some macrophyte species more resilient to changing water levels and increased nutrient concentrations than others? Can some establish/adapt more quickly than others?

- What impact would macrophyte reestablishment have on turbidity and nutrient cycling?
- What is the expected lag time for lake recovery following nutrient reduction?
- For warm water aquatic life, waterfowl, shorebirds, and water-oriented wildlife: where and when in Utah Lake are early life stages of fish present? Which species are most sensitive and need protection from nutrient-related impacts?
- Is there an improved stable state that can be reached under the constraints of current water and fishery management?
  - What would the current nutrient regime of Utah Lake be assuming no nutrient inputs from human sources? This question may require the identification of primary sources of nutrients.
  - Assuming continued carp removal and current water management, would nutrient reductions support a shift to a macrophyte-dominated state within reasonable planning horizons (i.e., 30- 50 years)?
  - If the lake stays in a phytoplankton-dominated state, to what extent can the magnitude, frequency, and extent of harmful and nuisance algal blooms be reduced through nutrient reductions?

3.0 INFORMATION NEEDS FOR NNC SETTING

3.1 KNOWLEDGE GAPS ASSOCIATED WITH NNC SETTING

The SP is planning to use multiple lines of evidence when deriving NNC for Utah Lake. Approaches will include: empirical analyses to inform reference-based and S-R analysis; a mechanistic model to inform reference and S-R analysis; and literature reviews to inform the scientific literature line. Each component is described in greater detail in Tetra Tech (2019b). As with the charge questions, knowledge gaps need to be identified and addressed to improve the SP’s ability to derive scientifically defensible NNC. Many of the data gaps for setting NNC overlap with the information needs for the charge questions (described in Section 2).

Table 4 summarizes the knowledge gaps affecting the lines of evidence that the SP is planning to use for NNC development. For the empirical analyses (S-R approach), nutrients (N and P) are the causal drivers and the assessment endpoints that are currently being considered include cyanobacteria cell counts, chlorophyll-a, dissolved oxygen and potentially cyanotoxin concentrations. Most of these endpoints are recreation-based. Data analyses and ongoing research are being performed to address some of the knowledge gaps, which include questions such as: at what concentrations do cyanobacteria in Utah Lake affect HAB-related impairments for recreational and drinking water uses? at what point do chlorophyll-a concentrations become unacceptable for contact recreation by the public? Is DO limiting to aquatic life in Utah Lake? The SP is considering doing a user perception survey to help identify critical chlorophyll-a targets.

Two other primary lines of evidence will be based on simulations with a mechanistic model that is currently being built and calibrated by a research team from the University of Utah. It is a three-dimensional hydrodynamic model coupled with a water-quality model. The selected hydrodynamic model is the Environmental Fluid Dynamics Code (EFDC) and the selected water-quality model is Water Quality Simulation Program (WASP). Both models are supported by the US Environmental Protection Agency (EPA) and have been widely applied for numeric nutrient-criteria development and total maximum daily loads (TMDLs). Knowledge gaps arise due to limitations with the model itself as well as with the data going into the model. To better understand limitations with the model, we examined the causal conceptual model (Tetra Tech 2019c) and identified which parts are either not addressed by the model or are addressed to a limited degree. Figure 4 shows the conceptual model with areas of limitation marked by colored boxes. Examples of variables that are not modeled include turbidity, water clarity, food web processes, changes in food resources and habitat structure, and aquatic life and wildlife.

There are some known gaps and limitations with the model input data as well. Two areas that will likely need further research are sediment dynamics and the role of the food web on nutrient dynamics. After the ongoing sediment project is completed (Section 1.3), the SP will reevaluate research needs on sediment dynamics. For the food web, much of the information can be researched and estimates can be brought in (e.g., of nutrient exports from primary and secondary consumers), but those processes are outside the construct of the model and the SP is still debating whether the food web component is a necessary requirement for improving estimates of NNC. HABs and algal toxins may also need some additional research, but this depends in part on whether the SP decides to include toxins as an assessment endpoint. More research may also be needed to inform what inputs to use for the reference-based model runs (in which the model is set to minimal or no human contributions). This will be reevaluated by the SP after the paleo study (Section 1.3) is completed.

The other lines of evidence (direct observation (data collection) and scientific literature) will be used more as secondary considerations in NNC setting. Both have known limitations. The direct observation (reference-based approach) is limited because few data points from Utah Lake are suitable to be used as reference data, and comparable data from other lakes is difficult to find because Utah Lake is so unique. Utah Lake's unique nature also limits the applicability of values derived from scientific literature. Nevertheless, these two lines of evidence are valuable in that they can help place the proposed NNC values into the context of existing, established science. Depending on how the values compare, these comparisons may provide additional support for the SP's NNC recommendations or may prompt further inquiry.

Table 4. Knowledge gaps in the primary lines of evidence that are currently being considered.

Approach	**Line of evidence**	**How will it help inform NNC**	**Knowledge gaps**	**Being addressed**
Reference-based	Paleolimnological reconstruction of past conditions	Can inform what reference conditions were, whether conditions previously supported desired assessment endpoint conditions, if and how much such conditions have changed adversely, and whether such conditions are once again achievable	Historic phosphorus, N, and silicon concentrations	Paleo RFP
			Historic water quality, trophic state, and nutrient regime	Paleo RFP
			Can past diatom communities and macrophyte communities be detected in sediment cores? If so, what were those communities like?	Partially through the paleo RFP (at least with question 1, not sure yet about question 2)
	Model based prediction	The model will be set to minimal or no human contributions and model responses will be evaluated. This will help inform what achievable conditions might be	What are appropriate inputs to use for natural nutrient (N and P) loads?	Partially through paleo RFP, atmospheric deposition studies, and reference-based studies for tributary inputs.
	Direct observation	Provides context for other lines of evidence and can be used as a measure of baseline values for N and P	There are limited observed reference data from Utah Lake and few if any comparable reference lakes due to Utah Lake's unique features	Data analyses, to the degree possible (all data from Utah Lake have been compiled; data from comparable lakes may be evaluated as well)
Stressor-Response	Empirical	Can help identify nutrient concentrations where negative impacts to assessment endpoints become evident. N and P are the causal variables. Endpoints that are currently being considered are cyanobacteria cell counts, chlorophyll-a, dissolved oxygen and potentially cyanotoxin concentrations.	Endpoint #1: cyanobacteria cell counts. At what concentrations do cyanobacterial cell counts exceed 100,000/ml.	Data analysis and Mechanistic Modeling (all data from Utah Lake have been compiled; data from comparable lakes may be evaluated as well)
			Endpoint # 2: chlorophyll-a concentrations. Need to investigate at what point chlorophyll-a concentrations become unacceptable for contact recreation by the public. Which nutrient (N or P) is limiting? Does turbidity interact with nutrients to influence chlorophyll-a? How much P is biologically active? (need to investigate the relationship between primary productivity, pH and calcite)	Partially with data analysis and funded Bioassay and Sediment projects

Table 4 continued…

Approach	Line of evidence	How will it help inform NNC	Knowledge gaps	Being addressed
Stressor-Response	Empirical continued…	Will help identify thresholds where nutrient concentrations cause negative responses as measured by the assessment endpoints	Endpoint # 3: Dissolved oxygen. Is anoxia an issue in Utah Lake?	Data analyses, to the degree possible provided available DWQ data.
			Endpoint # 4: Cyanotoxin concentrations. Which cyanotoxins are present and what are their drivers?	Partially via data analysis and ongoing research.
			Endpoint # 5: biological endpoints (e.g., macrophytes, phytoplankton, invertebrates and fish)	Not currently
	Mechanistic model	Allows for exploration of multiple future scenarios to help support cause-effect relationships observed in the empirical S-R relationships. The model(s) can be used to generate N and P load targets that meet desired beneficial use conditions, which can then be translated into concentrations for assessment	There are limitations with the model itself - see Figure 4; the purple boxes show what is not covered by the model, and blue-dashed boxes show which items are only covered to a limited degree	Through ongoing and future model development
			Model Uncertainty. Are more novel approaches for model uncertainty advised?	To be discussed by SP.
			There are limitations with the data going into the model	Partially. Some, like the path step for wet and dry deposition are being improved through additional research. Others, like those related to water clarity and aquatic life, are not currently being addressed

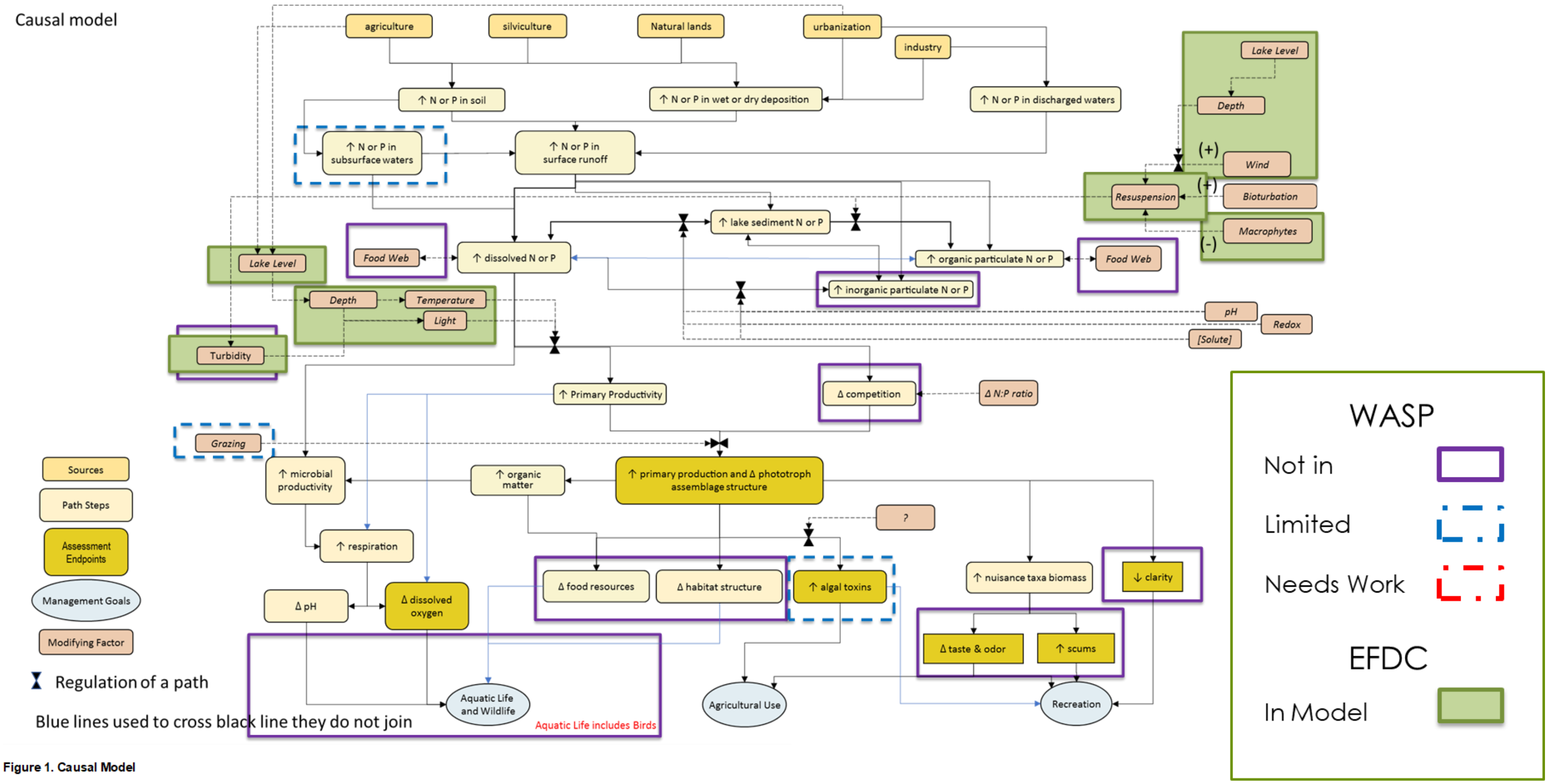


Figure 4. Causal conceptual model for Utah Lake. The purple boxes show what is not covered by the model, and blue-dashed boxes show which items are only covered to a limited degree.

3.2 SUMMARY OF MAJOR INFORMATION NEEDS

Identifying and addressing knowledge gaps for NNC setting will be an iterative, ongoing process. Below is a list of the SP's highest priority information needs that would improve their ability to recommend scientifically defensible NNC –

- Sediment dynamics – what knowledge gaps remain after the preliminary sediment study (Section 1.3)?
- Food web in nutrient dynamics – how important is this to setting NNC? If deemed important, how can this information be integrated into the NNC development process?
- Reference conditions – what were past conditions in Utah Lake (water quality, trophic state, and nutrient regime)? How do past N and P values compare to values coming out of the data characterization and S-R empirical analyses?

4.0 STRATEGIC RESEARCH PLAN

The SP is developing this SRP to address the information needs described in Sections 2 and 3 for answering the charge questions and setting NNC.

SECTION 4.1 PRIORITIES

Prioritization of research ideas has been an ongoing process for the SP throughout Phase 2 of the ULWQS. In February 2019, the SP brainstormed near-term research ideas to help address the charge questions critical to understanding the current state of Utah Lake with respect to nutrients and ecology.

The SP followed that up with a prioritization/ranking exercise, during which they refined the highest near-term priority ideas and wrote them up as specific projects in Requests for Proposals (RFPs). Three RFPs (bioassay, paleo and sediment) resulting from that effort were posted in May 2019 and are scheduled for completion in December 2020, January 2021, and May 2020, respectively.

A second round of brainstorming and prioritization was undertaken. During the December 2019 meeting, the seven members of the SP that were in attendance split into two groups and ranked the original research ideas that weren't addressed in the first round of RFPs. In addition, each group brainstormed several new ideas, which brought the total number of research ideas that are being considered to 19 (Table 5). During the meeting, the SP members used a modified Delphi method to come up with their rankings:

- Step 1: Rank right away – highest priority to least
- Step 2: Discuss/deliberate
- Step 3: Re-vote and report back

Results were compiled and overall rankings were calculated based on mean rankings. In late January 2020, SP members were given a follow-up online survey so that they could change their rankings if desired. The online survey also allowed SP members who were not able to attend the December meeting an opportunity to weigh in. Nine SP members participated in the online survey. Results are shown in Table 5. The top four research ideas remained consistent during both ranking exercises (shown in bold text in Table 5). The top ideas were further refined into specific projects through one-on-one conversations with SP members, as well as through an additional brainstorming session at the March 2020 SP meeting. As with the last round of prioritization, a subset of specific projects are being developed as RFPs, which will be posted as soon as they are ready and approved by the SP and SC to ideally take advantage of the next field season.

Table 5. Overall rankings of the 19 research ideas that are currently being considered by the SP. The top four ideas are shown in bold text. The February 2020 rankings came from eight SP members via an online survey, and the December 2019 rankings came from the prioritization exercise that seven SP members went through during the in-person meeting.

	Research ideas	Mean Ranking - Feb 2020	Mean Ranking - Dec 2019
1	**How large is internal vs external loading (how long would recovery take?)**	**2.3**	**1.9**
2	**Sediment budgets (C, N, and P; nutrient flux chambers)**	**3.6**	**3.9**
3	**Calcite scavenging (how bioavailable is SRP – does bioassay address?)**	**4.3**	**3.4**
4	**Adding modules to the WQ models (sediment diagenesis, calcite scavenging)**	**4.3**	**5.2**
5	Carp effects on nutrient cycling	7.3	
6	Lake level (effect on macrophytes)	9.2	9.0
7	Bioassays that incorporate sediment (next phase mesocosms)	9.4	
8	Macrophyte recovery potential (Provo Bay demo)	10.0	10.7
9	Lake-level effects on biogeochemistry and nutrient cycling	10.2	
10	Environmental controls on toxin production	11.1	
11	Turbidity effect on primary producers	11.2	10.6
12	Resuspension rates from bioturbation	11.7	
13	Carp effects on zooplankton (and does this influence algal response)	11.8	9.6
14	Carp effects on macrophytes	12.1	9.9
15	Toxin Production and N Species	13.7	12.3
16	Recreational surveys	13.8	9.6
17	Macrophyte role (to biogeochemistry)	14.0	11.1
18	Additional atmospheric deposition data*	14.6	
19	Alternative models (PCLake – cyano/macrophyte state change)	14.9	12.0

**Atmospheric deposition was deprioritized by the Science Panel, as it is expected that an ongoing atmospheric deposition study may preclude or reduce the need for additional work on atmospheric deposition. Existing atmospheric deposition data will be included in external load calculations for research idea 1.*

SECTION 4.2 SPECIFIC RESEARCH PROJECTS

4.2.1 Internal vs. external loading

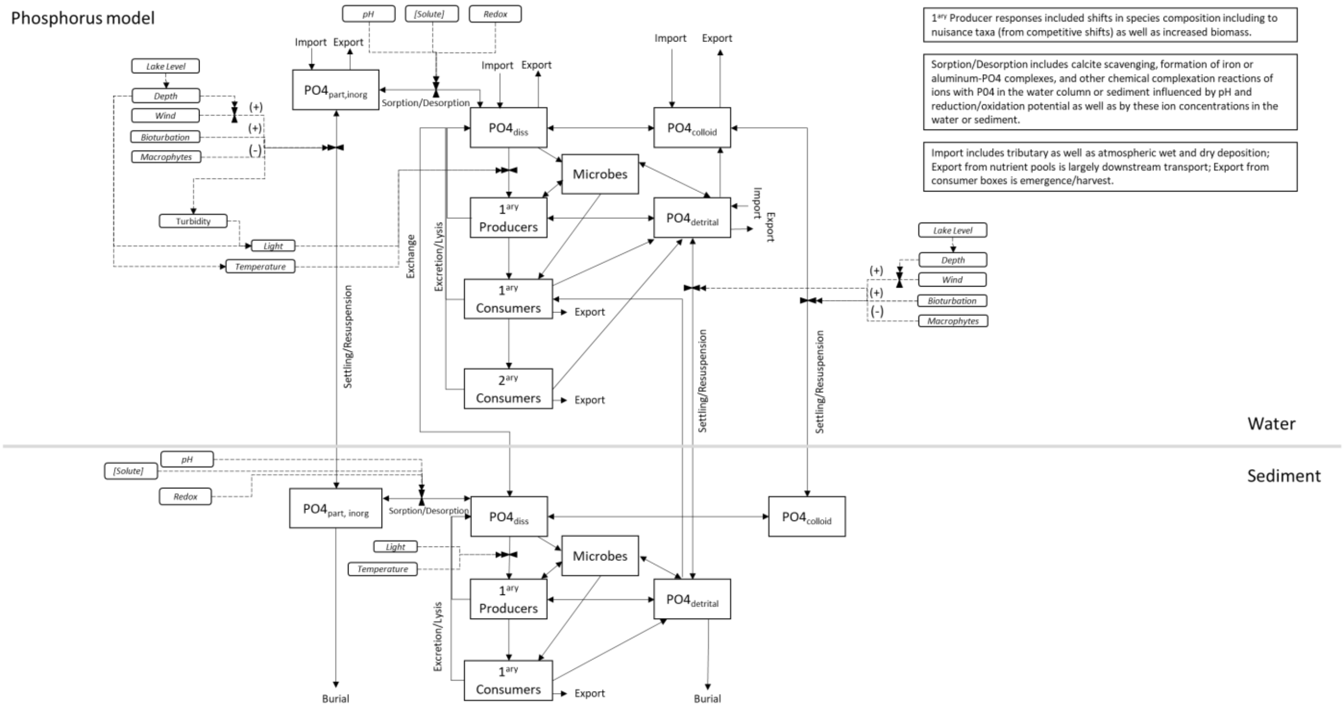
Note: This section also incorporates sediment nutrient budgets (section 4.2.2)

Problem statement

Utah Lake is a eutrophic lake that receives substantial loads of nutrients from watershed and wastewater treatment plant (WWTP) inputs. Previous studies have demonstrated the majority of nutrient loads are retained within the lake rather than exported by the Jordan River outflow (PSOMAS and SWCA 2007; Merritt and Miller 2016), demonstrating Utah Lake actively processes and stores nutrients. It is clear there is a large and actively cycling pool of N and P, which also interacts with C stocks. However, there are no known studies that have attempted to compile the known information about C, N, and P stocks and fluxes for the lake, especially the sediments.

Constraining the budgets of C, N, and P will allow for more informed management of water quality issues in Utah Lake. The balance of external inputs and outputs of nutrients, and the variability observed in this relationship, informs the role of Utah Lake as a nutrient processor and sink. Preliminary evidence suggests that algal productivity may be co-limited by both N and P, necessitating a synthesis of knowledge about both nutrients. A major step forward in our understanding of nutrient dynamics in Utah Lake will be to define and quantify (1) the balance of inputs and outputs, (2) the key processes responsible for transformations and within the lake, particularly those that involve exchanges across the sediment-water interface, and (3) the mediating factors that impact the magnitudes of sources and sinks. While the external loads to the lake are well-defined, the processes responsible for internal cycling are not. Further, bioavailable pools of nutrients need to be separated from total pools to determine the magnitude of active cycling within the biotic community.

A conceptual model of pools and processes associated with N and P was developed by Tetra Tech (Figures 1 and 2). A literature review will allow us to amend the conceptual model with existing estimates of magnitudes for these stocks and fluxes. Components of C, N, and P cycling that have not been quantified in Utah Lake can be amended with estimated values from the literature. A synthesis of the known components of the stocks and fluxes of these elements will then enable us to apply a model such as SedFlux to the lake. Lastly, this synthesis will allow us to determine key gaps in understanding and how to fill them, namely rates and stocks that can be leveraged from studies in comparable systems vs. those that should be measured directly in future Utah Lake research.

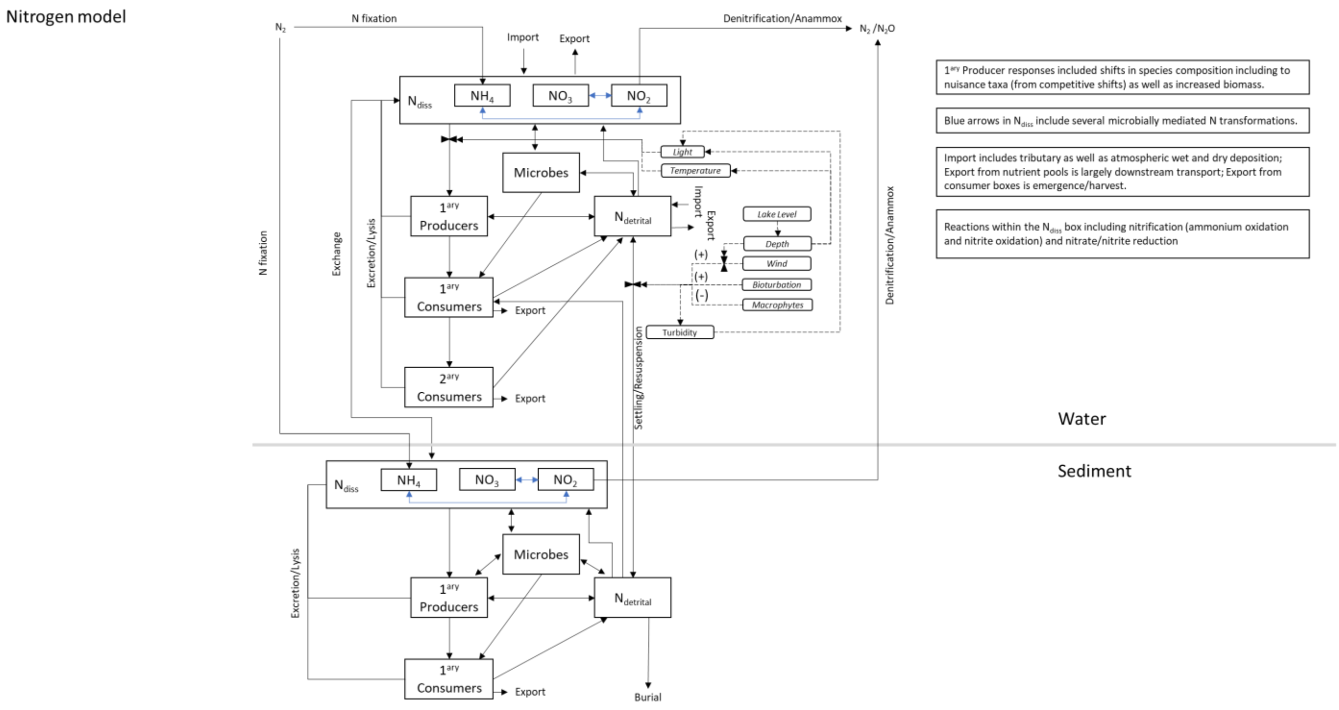


1^{ary} Producer responses included shifts in species composition including to nuisance taxa (from competitive shifts) as well as increased biomass.

Sorption/Desorption includes calcite scavenging, formation of iron or aluminum-PO4 complexes, and other chemical complexation reactions of ions with P04 in the water column or sediment influenced by pH and reduction/oxidation potential as well as by these ion concentrations in the water or sediment.

Import includes tributary as well as atmospheric wet and dry deposition; Export from nutrient pools is largely downstream transport; Export from consumer boxes is emergence/harvest.

Figure 5. Conceptual model of phosphorus pools and processes in Utah Lake.



1^{ary} Producer responses included shifts in species composition including to nuisance taxa (from competitive shifts) as well as increased biomass.

Blue arrows in N_{diss} include several microbially mediated N transformations.

Import includes tributary as well as atmospheric wet and dry deposition; Export from nutrient pools is largely downstream transport; Export from consumer boxes is emergence/harvest.

Reactions within the N_{diss} box including nitrification (ammonium oxidation and nitrite oxidation) and nitrate/nitrite reduction

Figure 6. Conceptual model of N pools and processes in Utah Lake.

Existing Data and Information

Previous work has applied the Utah Lake Water Quality Salinity Model (LKSIM), a hydrodynamic model that balances hydrologic inputs and outputs for streams, springs, groundwater, drains, precipitation, and evaporation. PSOMAS and SWCA (2007) presented a hydrologic budget of all inflows and outflows, broken down by both monthly and annual averages. This LKSIM application also included TP loads for each inflow and outflow with the same temporal resolution. A major finding of this study was that inflow TP loads (average 297.5 tons/yr) are substantially higher than outflow loads (average 83.5 tons/yr), and that WWTPs make up the majority (76.5 %) of TP loading to the lake, in comparison to loading from inflow tributaries (20.7 %). An additional LKSIM-based study by Merritt and Miller (2016) demonstrated similar results, showing that 90 % of P loading and 84 % of N loading is retained by the lake. The hydrology of Utah Lake was modeled for a different set of years (2009-2013), broken down by year and input type (individual rivers, groundwater, precipitation). Further analysis of this dataset has been provided by Brett (2019). A study currently underway by O'Bryant and Daly (2020) builds on previous mass balance studies to provide the latest estimates of water budget and nutrient loading to the lake. These studies set the stage for a well-constrained budget of N and P inputs and outputs for Utah Lake, but the black-box approach limits knowledge about within-lake processing.

C, N, and P budgets, particularly as they relate to bioavailable stocks and transformations, are relevant to direct management activities in Utah Lake. Nutrient inflows to the lake have an N:P ratio of 8:1 which would typically indicate N limitation on primary productivity, but Merritt and Miller (2016) propose that concentrations of both elements are sufficiently high to be non-limiting. Elemental stocks are bound in biomass across trophic levels (Gaeta et al. 2019), and biotic interactions will be a key component of the C, N, and P budgets to quantify.

A study underway by Goel et al. demonstrates that sediments are a critical component of N and P cycling in Utah Lake. Under in situ conditions, sediments are a sink for soluble reactive P and ammonium and a source of total dissolved P. This experiment captured the water column equilibrium P concentration (EPC_0) at which the sediments change from a source to a sink of P, an important aspect to define for the purposes of quantifying internal loading rates of P. Further manipulations of oxygen concentrations and pH suggest that calcite formation is an important sink for P and that redox and pH represent key modulating factors for sediment fluxes. A closer review of these rates in context with the literature will help to quantify the processes responsible for fluxes at the sediment-water interface.

A preliminary Google Scholar search yielded seven studies that have directly addressed C, N, and/or P in Utah Lake (Bradshaw et al. 1973, Merrell 2015, Abu-Hmeidan et al. 2018, Olsen et al. 2018, Olsen et al. 2018, Hogsett et al. 2019, Randall et al. 2019). These studies address topics ranging from external loads to biological and chemical transformations to sediment stocks. A more thorough literature review will be conducted as part of Task 1, outlined below, through a combination of a Web of Science search and a citation network.

Additional studies based on other lakes and reviews of lake nutrient budget methodologies will supplement analyses, including Larsen and Mercier (1975) and Brett and Benjamin (2008).

Study Objectives

The objective of this research is to address the shortcomings identified in the problem statement and to support the Science Panel in addressing questions about the current state of the lake with respect to nutrients and ecology (Science Panel charge question #2). More specifically, this research will help inform the following charge questions:

- What is the current state of the lake with respect to nutrients and ecology? (Science Panel charge 2)
- What are current sediment equilibrium P concentrations (EPC) throughout the lake? What effect will reducing inputs have on water column concentrations? If so, what is the expected lag time for lake recovery after nutrient inputs have been reduced? (Science Panel charge 2.4.i)
- What is the sediment oxygen demand of, and nutrient releases from, sediments in Utah Lake under current conditions? (Science Panel charge 2.4.ii, Attachment B)
- What would be the current nutrient regime of Utah Lake assuming no nutrient inputs from human sources? (Science Panel charge Future High Level Questions a)

Study objectives are to:

1. Compile a mass balance of the external inputs and outputs of C, N, and P for Utah Lake.
2. Compile all known data on standing stock and flux rates for C, N, and P in Utah Lake, specifically with regard to:
    a. Water column processes
    b. Sediment processes
    c. Spatial differences and variability
3. Create a mass balance model for each element that incorporates information from objectives 1 and 2 and a quantification of uncertainty around estimates.
4. Identify major gaps and uncertainties in existing data and propose future studies to fill these gaps

Expected Outputs and Outcomes

Specific outputs are expected to include, but are not limited to, a summary of existing literature, a mass balance model for each element, a conceptual model that includes magnitudes of standing stocks and fluxes, and a technical report with detailed findings for all tasks. All data for this work will be made available to the Science Panel per the deliverable dates schedule in section 5 of this Scope of Work.

When the work is completed, the Science Panel will have a greater comprehension of the knowns and unknowns of C, N, and P standing stocks and fluxes in Utah Lake and a study plan for how to fill data gaps. With this information, the Science Panel will have a greater certainty around:

- The inputs and outputs of C, N, and P to and from Utah Lake
- The relative and absolute roles of water column and sediment in the cycling of C, N, and P
- The actively cycling pools of C, N, and P and how these relate to the hydrology and biology of the system
- Nutrient budgets for Utah Lake that can inform future predictions of management scenarios

Capacity to Address with Mesocosms

After identifying knowledge gaps, mesocosms may be proposed as future studies to fill gaps.

4.2.2 Sediment budgets (C, N, and P; nutrient flux chambers)

Note: sediment budgets have been incorporated into section 4.2.1. Nutrient flux chambers may be proposed as future studies to fill knowledge gaps.

4.2.3 Calcite scavenging

Problem statement

P loading is a major water quality issue in lakes, and P uptake by sediments may temporarily or permanently remove P from the water column. Sorption of P onto various cations may occur, including aluminum (Al) and iron (Fe) under acidic conditions and calcium (Ca) and magnesium (Mg) under alkaline conditions (Reddy et al. 1999). The major process(es) governing P binding vary by system and may be controlled by substrate availability, pH, redox, and sulfate (House and Donaldson 1986, House 1990, Caraco et al. 1999, Reddy et al. 1999). The reverse of these binding reactions may occur, with sediment release occurring when favorable environmental conditions reverse.

Calcite binding is an inorganic reaction whereby P is adsorbed to calcite and precipitates. This reaction is favorable under high water column pH, and high Ca^{2+} and P concentrations (House and Donaldson 1986, House 1990). The size of calcite granules may impact the degree of P binding as well (Berg et al. 2004). Although calcite precipitation is an inorganic reaction, biotic processes can affect rates of the process, most notably photosynthesis and respiration which alter pH (Hartley et al. 1997). Calcite precipitation is a major P sink in many lakes (Hamilton et al. 2009 and references therein) and may represent a semi-permanent P sink in waters with high Ca^{2+} and alkalinity (Reddy et al. 1999). Adding calcium hydroxide to induce calcite precipitation has been used as a management technique as well (Dittrich and Koschel 2002).

Mass-balance data suggests that Utah Lake acts as a nutrient (P) sink. 90% of external P loading to Utah Lake is retained within the lake (Merritt and Miller 2016), though the response of in-lake P concentrations to external P inputs suggest this sink may be variable (Brett 2019). One probable mechanism for the P sink is calcite binding, as demonstrated in a recent sediment core experiment by Goel et al (2020). However, Randall et al. (2019) demonstrate sediment-bound P exists in different sediment fractions as well, including Fe oxides. Although likely sediment-bound P fractions have been identified through sequential chemical extractions, specific mineral forms have not been quantified. Further, the reactions driving P binding, including magnitude and environmental drivers (e.g., pH, P, cations), have not been fully described.

Utah Lake sediments may switch from a sink to a source of P in response to a decrease in water column P concentrations below the equilibrium concentration. The timescale of eventual equilibration between the sediment and water column is likely to not only depend on the gradient of water column vs. sediment concentrations but also the degree of sediment resuspension and the amount and chemical forms of P in the sediment (Reddy et al. 1999). Further, nutrient criteria often focus on total P, including fractions of P that are unavailable to primary producers such as calcium phosphate. By developing a more thorough knowledge of P binding and speciation in Utah Lake, the sediment P sink can be better quantified and the forms of P available to support primary production will be better defined.

- Currently the speciation of P in the water column and sediments of Utah Lake is not well characterized. Specifically, it is not clear what fraction of P is bound to calcite and to other sorbing substances (e.g. Fe, Mn).
- Currently, it is not clear how to predict P speciation and binding under varying water quality conditions (e.g. pH, redox), such as through sorption isotherms and/or partition coefficients.
- Currently the factors impacting P speciation in the water column and sediments of Utah Lake are not well characterized. Specifically, it is not clear to what degree and under what conditions P binding may be reversible.
- Currently it is not clear which forms of P are bioavailable in Utah Lake and how that bioavailability is impacted by P binding.

- Currently it is not clear how to predict the impact of spatial and temporal changes in Utah Lake under existing conditions (e.g., as a result of productivity, seasonal variations, etc.) and under future conditions (e.g., as a result of lake management) on the factors impacting the fate, transport and bioavailability of P.

Existing Data and Information

Several existing and ongoing studies will address calcite P binding. The paleolimnological study will quantify sediment P fractions including calcite-bound P to recreate historical water column P concentrations (detailed findings not available at this time). The bioassay study will quantify current P concentrations in the water column including total P and soluble reactive P fractions (detailed findings not available at this time). The sediment core experiments by Goel et al. (2020) provided evidence for active calcite scavenging and help to form a basis for current knowledge and a path for future research. Randall et al. (2019) report concentrations of sediment P across Utah Lake, highlighting proximity to WWTP effluent and Provo Bay as locations with high sediment P. Across the lake, sediment P_2O_5 concentrations were positively associated with organic matter, CaO, and Fe_2O_3. 41-61 % of sediment P was associated with BD (bicarbonate/dithionite) fraction, representing Fe and Mn compounds, and 25-47 % was associated with the HCl fraction, representing Ca-phosphate minerals or acid-soluble organic P. Although Fe made up a small percentage of sediment mineral content, Fe retained approximately half the sediment P in oxide minerals. Although calcite is of major interest as a P sink in Utah Lake, previous work suggests that other mineral fractions and binding/release processes are important to fully characterize the system.

Study Objectives

The objective of this study will be to address the shortcomings identified in the problem statement and to support the Science Panel in addressing questions about the current trophic state of the lake with respect to nutrients and phytoplankton ecology (Science Panel charge question #2). More specifically, this research will help inform charge question 2.3.5: What is the role of calcite “scavenging” [i.e., binding] in the phosphorus cycle? Study objectives are divided into three phases.

Phase 1: Mineralogy

- Characterize the chemical speciation of P in the water column and sediment, including free forms, soluble complexes, precipitates, and sorbed species under a series of specified water quality conditions representing existing and potential future conditions in Utah Lake.
- Create a reaction network of processes involving the chemical species of P in Utah Lake.
- Characterize P scavenging and release from the water column and sediments under a series of specified conditions (e.g., pH, redox, etc.) in order to identify contributing mechanisms such as precipitation and sorption and estimate of the expected fractional distribution of P in each form.
- Evaluate the kinetics of P sorption and desorption of P onto sorbing surfaces (e.g., calcite, Fe, Mn, organics) and evaluate desorption hysteresis (e.g., speed or irreversibility of desorption and under what conditions) for a series of relevant conditions for Utah Lake.
- Evaluate predictive relationships to characterize binding of P onto sorbing surfaces in the water column and sediments such as using sorption isotherms and/or partition coefficients over a range of specified conditions (e.g., pH, redox, etc.).

Phase 2: Knowledge synthesis

- Synthesize knowledge from mineralogy study and previous/ongoing studies
- Interpret how previous work on extractable P fractions relates to mineral P forms
- Evaluate which study outcomes can inform environmentally relevant conditions and how
- Identify remaining knowledge gaps regarding sediment P binding and release

Phase 3: Fill knowledge gaps

- Address remaining knowledge gaps identified in phase 2
- Determine which chemical forms of P are bioavailable and their concentrations in the dissolved, colloidal, and particulate fractions
- Predict the impact of changing external P loading on the binding and release of sediment P
- Predict the extent and timescale of water column-sediment P equilibration in response to P management
- Apply P chemical species and reactions to process models for Utah Lake, including EFDC-WASP

Expected Outputs and Outcomes

Specific outputs are expected to include, but are not limited to:

- Phase 1: summary of relevant literature and data, a sampling and analysis plan (SAP), the project dataset, and a technical report with detailed results for all tasks.
- Phase 2: reports of knowledge synthesis and knowledge gaps
- Phase 3: summary of relevant literature and data, SAP (if applicable), the project dataset (if applicable), and a technical report with detailed results for all tasks.

All data collected for this project must be made available to the Science Panel per the deliverable dates schedule in Section 6 of this RFP. When this study is completed, the Science Panel will be able to answer the study objectives listed above and understand, with greater certainty:

- The chemical forms and amounts of P in the water column and sediment
- The relevant reaction network of P-relevant processes
- The conditions under which sediment P binding and release occurs, and the timing and spatial extent of these conditions in Utah Lake

Results from this study will also shed light on the capacity for internal P loading to support primary production and the potential impacts of P management on in-lake P cycling.

Capacity to Address with Mesocosms

This study focuses on mineralogy analysis, data analysis and modeling, and potentially algal bioassays. It is anticipated that mesocosms will not be an ideal method to address these study objectives.

4.2.4 Adding modules to the WQ models (sediment diagenesis, calcite scavenging)

Problem statement

EFDC-WASP was chosen as the Utah Lake nutrient model due to its ability to characterize the desired level of complexity while also having the flexibility, transparency, and compatibility to include modules needed for the Utah Lake context (von Stackelberg 2016). Sediment diagenesis and calcite scavenging were identified as important processes to model in Utah Lake, and EFDC-WASP has the capabilities to add these processes as submodules. However, adding key sediment functionality to the model requires modifications to the source code which have not been incorporated to date.

Existing Data and Information

In a UDEQ report, von Stackelberg (2016) notes that simulating P sorption dynamics, especially those that are dependent on pH such as calcite scavenging, require modifications to the source code of EFDC-WASP. Applications of EFDC-WASP in other systems have added sediment diagenesis and more complex P cycling, demonstrating the capability to add them to the Utah Lake application.

Study Objectives

1. Simulate sediment diagenesis and calcite scavenging in the Utah Lake application of EFDC-WASP

Expected Outputs and Outcomes

The successful addition of sediment diagenesis and P binding/release (generated from the study proposed in section 4.2.3) to the EFDC-WASP application to Utah Lake will more accurately characterize the biogeochemistry of the system, with regard to both processes at play and the magnitudes of elemental transformation and exchange. The primary output of this study will be a model report detailing the results of model calibration and validation for the new modules, and a summary of the findings.

Capacity to Address with Mesocosms

This study is focused on a process-based model, thus not necessitating mesocosms. However, mesocosm experiments from other studies laid out in this document may aid in the calibration of the EFDC-WASP model.

4.2.5 Carp effects on nutrient cycling

Problem statement

PSOMAS and SWCA (2007) and Merritt and Miller (2016) estimate external P loadings to the lake amount to an average of 247,000 and 270,000 kg P/year, respectively. Carp excretion of P, based on fish size, Utah Lake carp population density, and a regression analysis of P excretion and average carp dry mass, is estimated between 51,000-117,000 kg P/year, amounting to 19-48% of external P loads. Despite the variability in this estimate, carp clearly have the capacity to recycle a substantial amount of P in Utah Lake. At any one time, the P cycling through the carp population could be bound in biomass or released into various bioavailable and non-bioavailable forms. Similar estimates for N excretion using a similar methodology were between 496,000 and 1.1 million kg/year, supporting evidence from other systems suggesting substantial N contributions from excretion as well (e.g., Oehme et al. 2007). Further work is needed to determine the quantity and quality of nutrient cycling through the carp population, which would be aided by direct study to ground truth existing theoretical calculations.

Existing Data and Information

Carp excretion data, including individual carp excretion rates, have been provided by M. Vanni. Additional published data include carp size in Utah Lake (Gaeta and Landom 2016), fish wet:dry ratios (Cresson et al. 2017), and carp density estimates for Utah Lake (Gaeta et al. 2019), estimated at 7.5 million mature carp and 10 million juvenile carp.

Study Objectives

1. Quantify the rates of N and P uptake and release by the carp population in Utah Lake
2. Characterize the bioavailability of N and P excreted by carp
3. Predict the changes in lake N and P cycling in response to carp biomass reductions

Expected Outputs and Outcomes

The outcomes of this study will provide a well-constrained estimate of the role of carp on the nutrient budget of Utah Lake, in terms of both quantity and quality. Outputs may include a literature review, theoretical calculations, and field experiments.

Capacity to Address with Mesocosms

Carp could be included in mesocosms but might not be necessary given that there are other papers looking at carp in Utah Lake (Miller and Crowl 2006, Miller and Provenza 2007). Mesocosms could aid in the achievement of all three objectives for this project.

4.2.6 Lake level effects on macrophytes

Note: this project and the project described in section 4.2.8 have a great deal of overlap and combining them could be considered.

Problem statement

Although Utah Lake historically supported a large macrophyte population, a combination of factors including nonnative fish introduction and damming of the lake outlet led to a dramatic decrease in submerged aquatic vegetation (Janetski 1990). Macrophyte restoration presents several potential benefits for Utah Lake, including improvements in water clarity (James et al. 2004, Chao et al. 2010) and habitat for macroinvertebrates and fish (Landom et al. 2019). However, successful restoration may be impeded by several factors. Utah Lake experiences seasonal and interannual changes in lake level that cause large areas of the littoral zone to periodically dry, potentially desiccating macrophytes in the process. In addition, the water column is characterized by high levels of turbidity, which impedes light penetration to the benthos in permanently inundated areas and may prevent the establishment of macrophytes. Changing lake levels may thus have an effect in permanently inundated areas as well by impacting depth-dependent light penetration. Successful reestablishment of macrophyte communities will depend on a detailed understanding of lake-level effects on macrophyte survival in both littoral and permanently inundated zones.

Existing Data and Information

Landom et al. (2019) surveyed macrophytes across several transects of Utah Lake in 2016-2018. They found lake level changes explained some but not all the variability in macrophyte coverage. Lower lake levels (and thus shallower depths) during critical life stages such as germination may help macrophytes to establish (Liu et al. 2017), which was supported by the fact that macrophytes were only found in shallow areas. However, existing data suggest that low lake levels are beneficial only to a certain point. Marked reductions in macrophyte coverage were found in Powell Slough, Skipper Bay, and Provo Bay when lake levels dropped below compromise elevation.

The amount of benthic primary production is negatively correlated with k (Ask et al. 2009), consistent with the lack of macrophyte presence in Utah Lake. The question remains: in the current light environment, is it possible for macrophytes to establish? For submerged macrophytes, the light compensation point (PAR level at which photosynthesis matches respiration and net growth is zero) can help predict potential limitations on colonization depth. Madsen et al. (1991) demonstrated compensation points between 10 and 40 µmol m^{-2} s^{-1}, the majority of which were < 20. *Ceratophyllum demersum*, a submerged macrophyte found in Utah Lake (Landom et al. 2019), was found to have a light compensation point of 7.2 µmol m^{-2} s^{-1}, within the range of compensation points for seven species (95 % confidence interval = 6.9 ± 1.9 µmol m^{-2} s^{-1}; Sand-Jensen and Madsen 1991). Assuming a light compensation point of 10 µmol m^{-2} s^{-1}, 22 % of sampled light conditions in Utah Lake are below the compensation point, compared to 26 % at a compensation point of 20 µmol m^{-2} s^{-1} and 18 % at a compensation point of 7 µmol m^{-2} s^{-1}. A light compensation point of 10 µmol m^{-2} s^{-1} was entered into a logistic regression, which showed increased probability of a sample being below the light compensation point with increasing depth (Figure 7). Time of year had a significant effect as well. The probability of being below the light compensation point was 5 % at 1 m depth, 23 % at 2 m depth, and 61 % at 3 m depth. The depth at which there were equal odds of being above and below the compensation point was 2.73 m. These results suggest that shallow zones may be the best option for macrophyte restoration. However, colonization depth may be somewhat independent of transparency, as macrophytes may grow taller to harvest light near the surface (Middelboe and Markager 1997), and similarly may overcome late-season decreases in water transparency through early season growth. As detailed in the previous section, macrophyte establishment is predicted to decrease sediment resuspension events, potentially resulting in clearer waters and activating a positive feedback loop for macrophyte restoration.

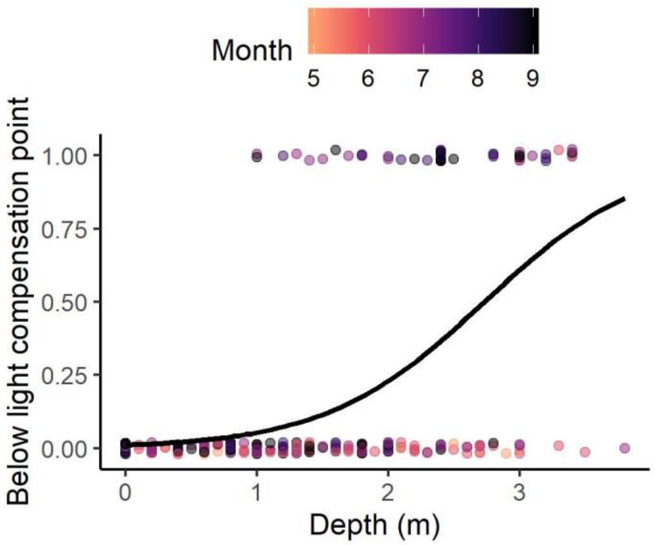


Figure 7. Logistic regression of water depth and samples above and below the light compensation point (0 and 1, respectively). The light compensation point was set at 10 µmol m^{-2} s^{-1}. The solid line represents the probability of a sample being below the light compensation point. Note: y axis values are either 0 or 1, but points are jittered to enable visualization of overlapping points.

Study Objectives

1. Determine lake level-related factors that either impede or support macrophyte re-establishment
2. Investigate the impacts of lake level fluctuations and periodic drying and wetting on macrophyte growth in littoral zones of Utah Lake
3. Investigate the impacts of lake level fluctuations and subsequent effects on light attenuation on macrophyte growth in open water zones of Utah Lake.

Expected Outputs and Outcomes
This study will shed light on the factors regulating macrophyte growth and recovery potential, as they relate to lake-level changes. Estimates of best-suited locations and depths for macrophyte restoration, along with measures of uncertainty, are expected as a component of the outcomes. A report of the results of literature review, theoretical analysis, field observations, and/or experiments is expected as the main output.

Capacity to Address with Mesocosms
Multiple methods may support the objectives of this study, including in-lake transects, mesocosms, and laboratory studies. Mesocosms present the opportunity to manipulate depth, drying, and turbidity effects across multiple treatments.

4.2.7 Bioassays that incorporate sediment (next phase mesocosms)

Problem statement
An ongoing study in Utah Lake addresses the following objectives via small *in situ* bioassays:

- Determine the nutrient limitation dynamics of Utah Lake (regarding P-, N-, or co-P and N limitation)
- Determine whether there is a seasonal dynamic to the above (i.e., P limitation leading to N limitation)
- Determine whether there is a spatial dynamic to the above

Achieving these objectives will provide key knowledge to fill data gaps related to limiting factors for primary production in Utah Lake. To fully characterize the factors driving primary productivity in Utah Lake and to effectively inform management activities, additional bioassays that build on the knowledge gained from the water column bioassays are needed. Factors not accounted for in initial bioassay experiments include sediment-water interactions, effects of turbidity, and water circulation. Additional study, scaled up to the mesocosm scale, could account for these factors.

Existing Data and Information
The Phase 1 report characterizes in-lake nutrient conditions and describes general linkages among trophic indicators, including nutrients. In the Phase 1 data analysis, chlorophyll-*a* and total P concentrations varied by site, with the highest concentrations in Provo Bay. Seasonal patterns in chlorophyll-a were observed, with peak algal growth in August through October. There were no clear seasonal patterns in total P or Secchi depth transparency (https://udwq.shinyapps.io/UtahLakeDataExplorer/). Further analysis of grab and sonde data by Tetra Tech, including examinations of wind, light attenuation, and turbidity, are underway. In addition, the Phase 1 bioassay experiments (as yet to be completed) are reporting on trends in nutrient limitation over space and time based on small *in situ* experiments.

Study Objectives

1. Investigate the interacting effects of light limitation, wind-driven resuspension of sediment, and sediment-water interactions with nutrient limitation on primary productivity
2. Evaluate the extent to which the findings of the first nutrient bioassay experiment (water column bioassays) are consistent with a second, larger mesocosm scale bioassay experiment (water column and sediment bioassays)

Expected Outputs and Outcomes
The primary outcome from this study will be a more complete understanding of the limnological and biogeochemical drivers of primary productivity in Utah Lake at a larger spatial scaled and incorporating sediment and atmospheric interactions. Specific outputs are expected to include, but are not limited to, a sampling and analysis plan (SAP), the project dataset from mesocosm experiments, and a technical report. All data collected for this project must be made available to the Science Panel

Capacity to Address with Mesocosms
This is a mesocosm based research project. Mesocosms offer the capacity to manipulate several experimental factors at varying levels simultaneously, including nutrients, light and wind conditions.

4.2.8 Macrophyte recovery potential (Small scale demonstration)

Note: this project and the project described in section 4.2.6 have a great deal of overlap and combining them could be considered.

Problem statement

As outlined in Landom et al. (2019) and references therein, the pre-settlement state of Utah Lake was one of abundant submerged vegetation. Macrophyte biomass has since decreased dramatically due to invasive carp introduction, fluctuations in lake level due to damming and irrigation, and eutrophication. Returning Utah Lake to a macrophyte-dominant system may require one or more of these factors to be returned closer to the pre-settlement state. Alternatively, specific sites that are well-suited for macrophyte restoration in their existing state could be identified.

As outlined in section 4.2.6, lake level may impact macrophyte re-establishment in shallow littoral areas by drying areas otherwise well-suited for macrophyte growth, and it may impact deeper areas through fluctuations in light availability at the sediment. Additional factors, including macrophyte species and algal competition may impact recovery as well. A logical next step to determine the potential effectiveness of macrophyte restoration efforts is to attempt to re-establish macrophytes across a range of relevant conditions.

Existing Data and Information

See section 4.2.6. Landom et al. (2019) also outline transects across Utah Lake with varying levels of macrophyte abundance.

Study Objectives

1. Determine conditions that promote success of macrophyte restoration in Utah Lake, and alternatively the conditions that limit restoration.
2. Identify locations in Utah Lake that are well-suited for a full macrophyte recovery effort, starting with one or more small scale mesocosm demonstrations.

Expected Outputs and Outcomes

This study will provide a road map for macrophyte re-establishment in Utah Lake, which may include (1) recommendations for management activities aligned with restoration efforts, (2) the ranges of specific conditions in Utah Lake that may support macrophyte growth, and (3) recommendations for specific locations that are well-suited for pilot restoration sites. A report of the results of literature review, theoretical analysis, field observations, and/or experiments is expected as the main output.

Capacity to Address with Mesocosms

Mesocosms are a well-suited setting in which to pursue study objectives associated with macrophyte recovery. Multiple plots may be set up for re-introduction, recovery, and monitoring of physical and chemical conditions. Mesocosms could be deployed over multiple seasons, depending on macrophyte species.

4.2.9 Lake-level effects on biogeochemistry and nutrient cycling

Problem statement

There is a high degree of annual variability in water levels in Utah Lake (Figure 1; CUWCD and Thurin 2007). The fluctuations result from a combination of natural and anthropogenic factors, including variable precipitation patterns, evaporation, upstream water use, and managed outflows. On average, lake levels vary by ~3-4 feet per year (measured as the difference between the minimum and maximum water level). Due to the shallow nature of the lake, which averages 9 feet deep when full, the fluctuating water levels cause major changes in water-edge location and lake characteristics.

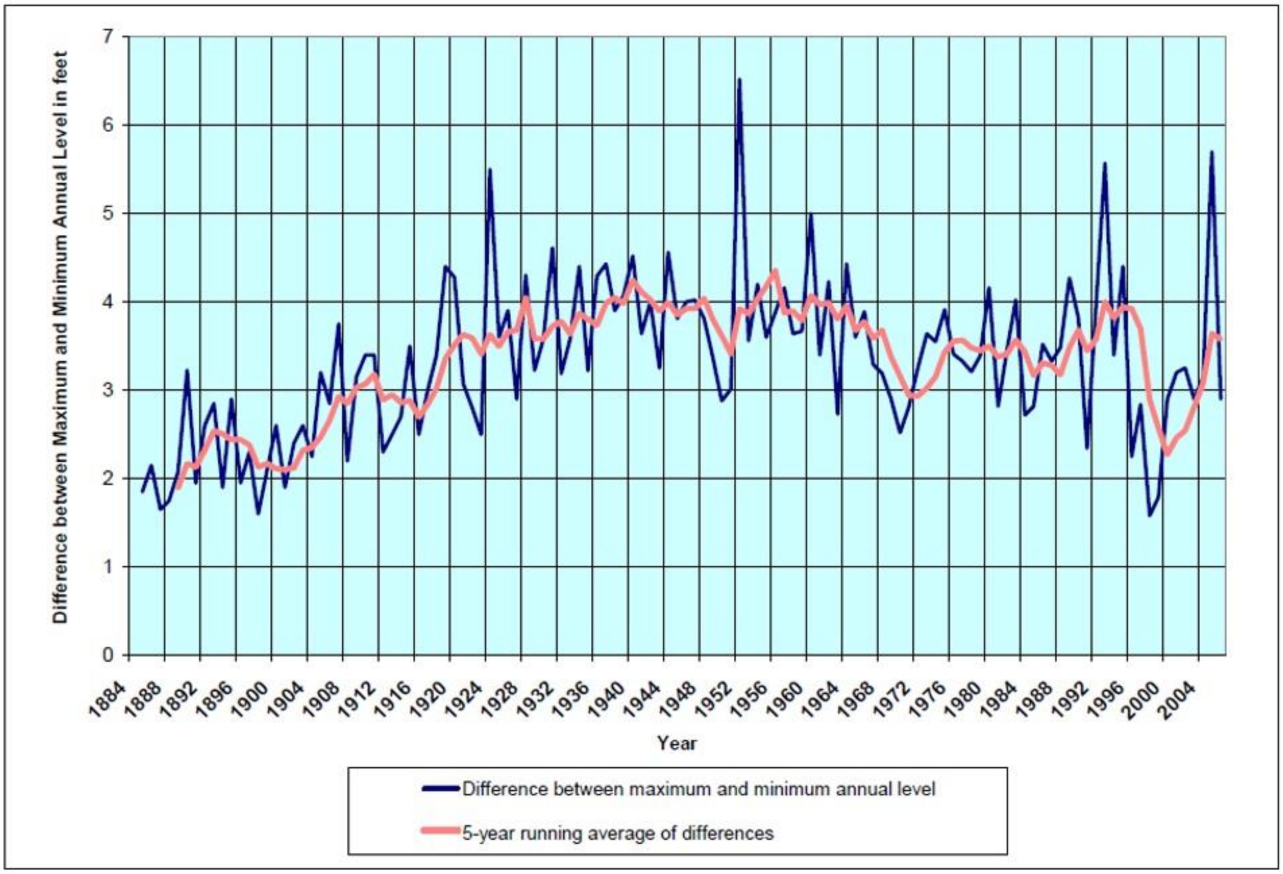


Figure 7. Annual and five-year average within-year variation in Utah Lake level from 1884 to 2006 showing generally increasing variation (doubling) over the historical period from 1884 to the 1930s to 1940 (from CUWCD and Thurin 2007; Figure 11).

With the large variations in lake levels and shallow depth, large expanses of Utah Lake's littoral sediments are subject to wetting and drying cycles of varying durations and frequencies. As littoral sediments go through periods of desiccation and inundation, it changes sediment properties and alters the duration of oxic and anoxic conditions, which in turn affects sediment oxygen demand, C, N and P release as well as microbial activity and composition (Weise et al. 2016). A number of studies have found that sediment drying promotes the release of potentially significant amounts of bio-available N and P on re-wetting (the so-called "Birch effect"; Birch 1960, McComb and Qiu 1998, Baldwin and Mitchell 2000, Scholz et al. 2002). This occurs as a result of numerous interacting processes, including enhanced aerobic microbial mineralization of OM and the reduction of nitrate, leading to an accumulation of ammonium N in the sediment; a decreased capacity of the sediments to adsorb nutrients such as P (Baldwin 1996); and the release of cell-bound nitrogen (ammonia) and filterable reactive phosphorus from sediment bacteria as they are killed during drying (Qiu and McComb 1995). Although both N and P may be released by these processes, they may respond differently, since the re-wetted sediments may have a reduced capacity to release P under anoxic conditions (which suggests that more N than P could be released into the water column on lake filling) (Mitchell and Baldwin 1998). The degree and duration of drying before rewetting has been shown to affect nutrient release. Schönbrunner et al. (2012) performed an internal phosphorus loading study in which floodplain sediments were exposed to different dry/wet treatments. They found that total phosphorus (TP) release from sediments into the water column increased with increasing duration of dry periods prior to rewetting and that repeated drying and wetting resulted in elevated phosphorus release. This effect was more pronounced when drying periods led to an 80% reduction in water content.

Sediment characteristics also affect nutrient releases. Shaughnessy et al. (2019) found that spatial distributions of lakebed nutrients in an agricultural reservoir in Illinois were predominantly controlled by sediment depositional patterns. The largest proportion of clay-sized particles and highest concentrations of OM were deposited near the dam wall and the highest proportion of (heavier) sand-sized particles were deposited near the river mouth. They found a significant and positive correlation between TP, TN, and TC with OM. Shaughnessy et al. (2019) also found that seasonal factors were important to consider. Nitrogen species varied seasonally at the sediment-water interface and were significantly higher during warmer weather/the growing season. The warmer conditions may enhance the release of nutrients from the sediments to the water column due to higher decomposition rates, higher pH due to photosynthetic activities, and low DO near the sediment-water interface that can change redox conditions so that reduced iron (Fe) might liberate P.

Little is currently known about the effects of water level fluctuations/wet and dry phases on C, N, and P loading from littoral sediments in Utah Lake. As the Science Panel works to respond to charge questions and nutrient criteria are being developed, it is important that this knowledge gap be addressed. More specifically, the Science Panel needs to better understand whether littoral sediments act as nutrient sinks (e.g., through denitrification, respiration and sedimentation) or sources (e.g., decomposition/mineralization and release upon rewetting), to what magnitude, and whether they reduce or enhance nutrient loads and impact the overall nutrient budget of the lake. The Science Panel also needs quantitative relationships between the duration and frequency on wetting and drying on nutrient loading in order to evaluate relationships between external and internal loads to Utah Lake.

Existing Data and Information

Water level data have been collected in Utah Lake since the late 1800's (Figure 1; CUWCD and Thurin 2007). A probability distribution of fluctuations in lake area using data from 2004-2018 estimated that the 5 to 95th percentile in lake area varied by 30 mi^2 from an average of 130 mi^2 (J. Martin, pers. comm). Based on other estimates, approximately 10-15% of the area is littoral. The extent of the areas of wetting and drying can also be illustrated by the numerical grid for the EFDC/WASP models being applied to Utah Lake (Figure 2) comparing areas that were always wet to those that were periodically dry. In either case, the amount of lake area potentially affected by wetting and drying is substantial. The duration of dry and wet phases can also be inferred from lake level data and can range from months to years.

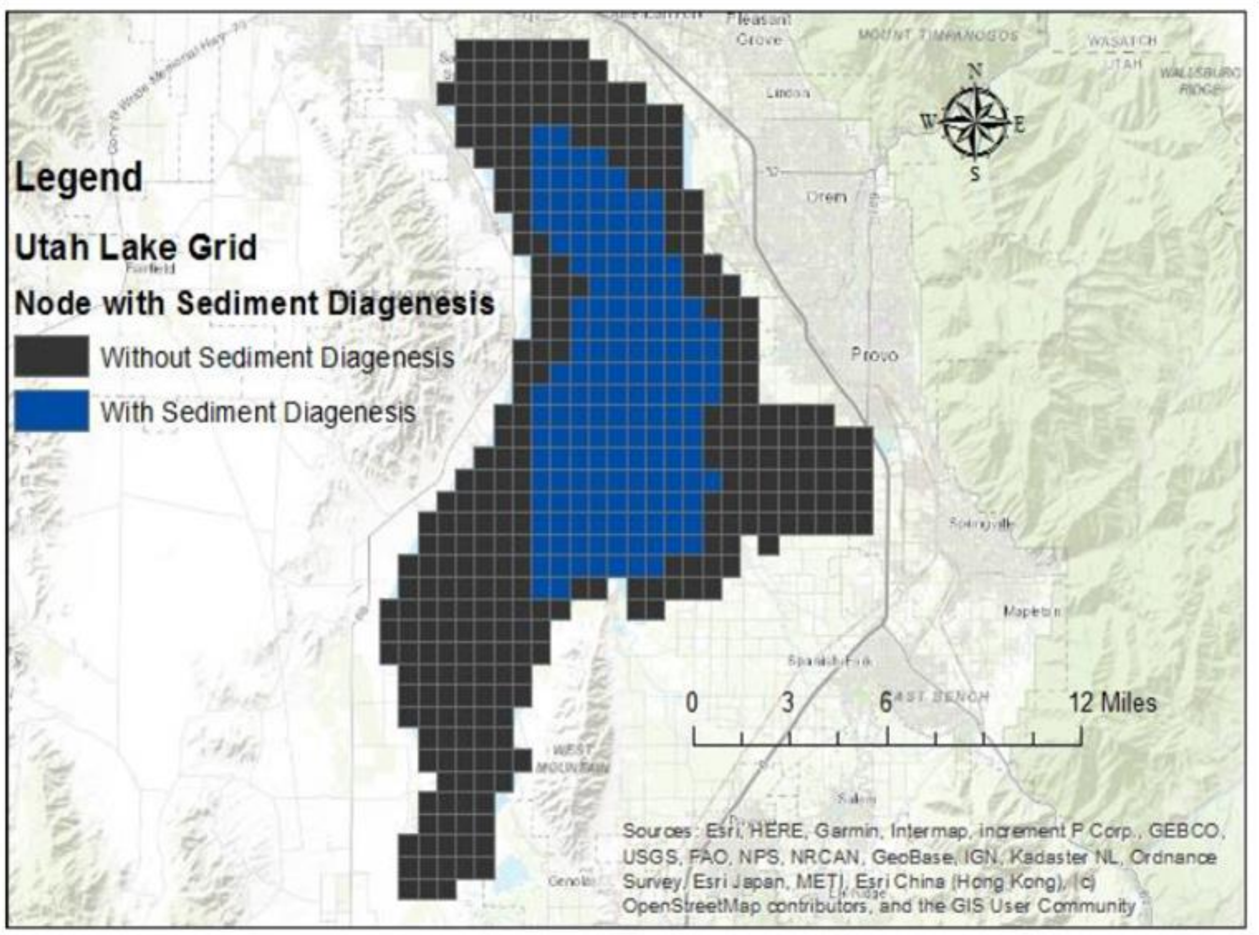


Figure 8. EFDC/WASP model grid comparing areas of Utah Lake that in simulations for the period of 2005-2015 that were continuously wet (blue; allowing simulation of sediment diagenesis) versus those that periodically became dry (black, sediment diagenesis was not simulated).

Other existing, complementary studies include a project that is currently underway on sediment–water-nutrient interactions in Utah Lake[1]. Results, which will be available in May 2020, will include calculations of sediment fluxes over a range of water column P concentrations and an exploration of the potential effects of changing pH, alkalinity, and redox. Equilibrium P concentration, the concentration at which the sediment switches from a sink to a source of P, may be derived from this study as well. It will also include estimates of sediment oxygen demand, as well as information on the role of sediment resuspension on nutrient releases or removal, primarily via calcite scavenging. The experiments were performed on wet cores collected from two sites —one site in Provo Bay and one site from the main body of the lake at an established DWQ monitoring site. These data could be contrasted with the results from this work, but also provide information on wet core nutrient content. Aside from that, little is known about littoral sediments in Utah Lake, thus the need for this work.

Study Objectives

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[1] this study is being performed on fully-wetted sediments, not sediments subjected to drying

The objective of this research is to address the shortcomings identified in the problem statement and to support the Science Panel in addressing questions about the current trophic state of the lake with respect to nutrients and ecology (Science Panel charge question #2). More specifically, this research will help inform the following charge questions:

- If there are linkages between changes in nutrient regime and Harmful Algal Blooms (HABs), what role if any does lake elevation change play? (Science Panel charge 2.3.iii, Attachment B)
- What is the sediment oxygen demand of, and nutrient releases from, sediments in Utah Lake under current conditions? (Science Panel charge 2.4.ii, Attachment B)

Study objectives are to:

- Conduct a thorough literature review of previous field, laboratory and modeling studies of the impacts of wetting and drying on sediment oxygen demand and nutrient cycling.
- Determine the spatial and temporal extent (duration and frequency) of wetting and drying patterns in littoral areas through Geographic Information System (GIS) analysis and evaluation of daily lake elevation data.
- Quantify the relationships (for Utah Lake) between the frequency and duration of dry periods on the subsequent oxygen demand and nutrient releases following re-wetting through field and laboratory studies.
- Quantify the rate and magnitude of nutrient (C, N, and P) fluxes following re-wetting over a range of sediment characteristics and wetting/drying treatments from littoral sediments.
- Develop quantitative relationships for estimating the oxygen demand and nutrient fluxes of re-wetted sediments as a function of the frequency and duration of periods of wetting and drying.

Expected Outputs and Outcomes

Specific outputs are expected to include, but are not limited to, a summary of existing literature, data, and anecdotal information on the effects of drying and wetting on lake littoral sediment nutrient flux, a sampling and analysis plan (SAP), the project dataset, and a technical report with detailed results for all tasks. All data collected for this project must be made available to the Science Panel per the deliverable dates schedule in Section **Error! Reference source not found.** of this RFP.

When this study is completed, the Science Panel will be able to answer the study objectives listed above and understand, with greater certainty:

- The role of littoral sediments subject to wetting and drying as sinks and/or sources of C, N, and P;
- Relationships between nutrient loads from those areas of the littoral zone subject to wetting and drying relative to other internal and external loads;
- The effects of varying patterns of drying/wetting (e.g., duration and extent) on C, N, and P flux from littoral sediments.

Capacity to Address with Mesocosms

This project is not planned to incorporate mesocosms. Mesocosm drying experiments could be conducted, however, to corroborate field findings or explore mechanisms.

4.2.10 Environmental controls on toxin production

Problem statement

Cyanobacterial blooms present public health hazards, most notably through the production of toxins. However, high cyanobacterial biomass is not always associated with high toxin concentrations, and vice versa (Giani et al. 2005, Wilhelm et al. 2011). This discrepancy suggests that factors that promote cyanobacterial growth may be different than factors that promote toxin production. For instance, while many cyanobacterial taxa can fix N from the atmosphere and can thrive under low N supply, a supply of bioavailable N can promote toxin production (Horst et al. 2014, Gobler et al. 2016). High N concentrations have been proposed as a driver of toxin production, supported in systems affected by harmful algal blooms including Lake Erie and Lake Mendota (Beversdorf et al. 2013, Steffen et al. 2014, Gobler et al. 2016). These findings have not been consistent across systems, with additional factors including relative N:P ratios, TP, pH, and temperature proposed as additional controlling factors

(Steffen et al. 2014 and references therein). Successful mitigation of toxin-related water quality threats in Utah Lake will depend on a more detailed understanding of the system-specific drivers of toxin production.

Existing Data and Information
Samples for microcystin and anatoxin-a have been taken several times in Utah Lake. These samples could be paired with concurrent water quality samples to determine preliminary empirical relationships.

Study Objectives
1. Investigate the chemical and physical driving factors for cyanobacterial toxin production in Utah Lake using a combination of field observations and laboratory experiments.
2. Quantify the relationship between cyanobacterial biomass and toxin concentration, along with any environmental covariates

Expected Outputs and Outcomes
As a result of this study, the environmental factors that promote toxin production will be known in more detail. Specific outputs are expected to include, but are not limited to, a summary of existing literature and data, a sampling and analysis plan (SAP), the project dataset, and a technical report with detailed results for all tasks. All data collected for this project must be made available to the Science Panel.

Capacity to Address with Mesocosms
To allow for maximum replication and experimental treatments, a microcosm approach may be better suited to this study than a mesocosm approach. However, once hypothetical controls are identified in laboratory settings, they could be tested in mesocosms using intentional cyanobacterial bloom manipulations.

4.2.11 Turbidity effects on primary producers

Problem statement
Utah Lake is a shallow eutrophic system that is also characterized by high turbidity. The occurrence of low light availability varies over time and space, with likely impacts on primary productivity through light limitation. Specific components of the primary producer community (i.e., phytoplankton, periphyton, macrophytes) are expected to respond differently to light limitation, and low light availability may favor specific species (e.g., buoyant phytoplankton) over others. A more complete understanding of the specific effects of turbidity and light availability on different components of the primary producer community will enable more informed decisions about managing eutrophication and restoring macrophytes in Utah Lake.

Existing Data and Information
An in-prep manuscript by King et al. addresses water clarity relationships with planktonic and benthic productivity in Utah Lake, finding that increasing water clarity by 0.3 m may be necessary to switch from planktonic to benthic dominance. Analysis of water quality data by Tetra Tech explores the relationships between light attenuation, chlorophyll, turbidity, and suspended solids, which could form the basis for an empirical analysis.

Study Objectives
1. Quantify the differential effects of light availability on individual components of the primary producer community
2. Investigate the impact of lowered turbidity on algal productivity and the re-establishment of macrophyte communities

Expected Outputs and Outcomes
Outcomes of this study will inform the specific responses of primary producers to turbidity and light availability. Specific outputs are expected to include, but are not limited to, a summary of existing literature, analysis of existing grab sample and sonde data, a sampling and analysis plan (SAP), the project dataset, and a technical report with detailed results for all tasks.

Capacity to Address with Mesocosms

Mesocosms present the opportunity to create multiple treatments across a range of light conditions to study primary producer response (macrophytes, benthic algae, and phytoplankton) and could be a beneficial addition to empirical analysis.

4.2.12 Resuspension rates from bioturbation

Problem statement
Carp abundance is associated with sediment resuspension and subsequent increases in turbidity (Breukelaar et al. 1994). Utah Lake is a naturally turbid system due to its shallow morphometry and fine-grained sediments, but the addition of carp to the lake has likely increased the degree of sediment resuspension. However, the degree to which sediment resuspension is a result of wind- or current-driven mixing or carp bioturbation is unknown. Establishing this distinction will inform expectations for reductions in turbidity that can be managed through carp reductions.

Existing Data and Information
Miller and Crowl (2006) address turbidity in their examination of carp effects on macrophyte and invertebrate communities in Utah Lake but do not quantify bioturbation directly. Additional studies have addressed the effects of common carp on sediment mixing depth and P mobilization in other shallow lakes (e.g., Huser et al. 2016), which may prove useful for generating estimates in Utah Lake.

Preliminary analysis by Tetra Tech has identified the conditions under which wind-induced mixing results in increased turbidity, which may help in parsing the effects of carp vs. physical mixing.

Study Objectives

1. Quantify the impacts of carp bioturbation on sediment resuspension and associated changes in turbidity and nutrient mobilization in Utah Lake
2. Differentiate the effects of carp bioturbation and wind- and current-induced mixing on sediment resuspension

Expected Outputs and Outcomes
A literature review will address the state of understanding of the impacts of carp on sediment resuspension in Utah Lake and expose gaps in knowledge. Follow-up observational and/or experimental study will fill those gaps. Outcomes of this study will inform the long-term expectations for zooplankton community structure and function as restoration efforts proceed. Specific outputs are expected to include, but are not limited to, a summary of existing literature, analysis of existing data, a sampling and analysis plan, the project dataset, and a technical report with detailed results for all tasks.

Capacity to Address with Mesocosms
Carp manipulations in mesocosms comparing gradients of density from recent historic to control would help quantify the density dependent effects of carp on water column turbidity.

4.2.13 Carp effects on zooplankton

Problem statement
Reducing the common carp population is a management goal that presents several benefits to the biogeochemistry and biotic communities in Utah Lake. Lower carp abundance is associated with lower sediment resuspension (Breukelaar et al. 1994), reduced internal nutrient cycling (Huser et al. 2016), and higher macrophyte biomass (Miller and Crowl 2006). Carp also have the capacity to affect the zooplankton community both directly through their omnivorous diet and indirectly through changes in turbidity and nutrient cycling. The effects of the carp population on zooplankton is of specific interest due to the trophic niche that zooplankton occupy; zooplankton graze on phytoplankton and can maintain low biomass and represent an important food source to fish populations including the June sucker. Carp-associated shifts in the zooplankton community include reductions in total biomass (Lougheed et al. 1998), changes in the biomass of specific zooplankton populations (e.g., rotifers, cladocerans, copepods; Radke and Kahl 2002, Cooke et al. 2009, Sass et al. 2014), and changes in body size of individuals (Radke and Kahl 2002). The specific impacts of carp on zooplankton may also depend on both carp and zooplankton density (Cooke et al. 2009). As carp reduction efforts in Utah Lake progress, it will

be crucial to both track changes in the zooplankton community and identify the mechanisms by which carp (or the absence thereof) affect zooplankton.

Existing Data and Information

Several reports from the June sucker recovery program address both carp and zooplankton, along with additional covariates. Gaeta and Landom (2016) found that zooplankton density was higher and body size was smaller with depth and higher P concentrations. They also suggest that carp removal effects may be confounded by drought and subsequent lake level reductions. The most recent report (Landom and Walsworth 2020) distinguished between the effects of carp and lake level, showing that lake level affected small-bodied zooplankton taxa but not large-bodied taxa. Carp reduction was associated with decreases in small-bodied taxa biomass but increases in large-bodied taxa biomass.

Previous mesocosm studies have addressed the effects of carp on macrophytes and invertebrates (Miller and Crowl 2006, Miller and Provenza 2007).

Study Objectives

1. Characterize the trends in zooplankton community structure over the time period of carp reduction
2. Identify the mechanisms and magnitudes by which carp impact the zooplankton community
3. Distinguish the impacts of carp from concurrent changes in Utah Lake, including lake level and macrophyte recovery
4. Predict the impacts of a shifting zooplankton population on phytoplankton and fish communities

Expected Outputs and Outcomes

A literature review will address the state of understanding of the impacts of carp on zooplankton in Utah Lake and expose gaps in knowledge. Follow-up observational and/or experimental study will fill those gaps. Outcomes of this study will inform the long-term expectations for zooplankton community structure and function as restoration efforts proceed. Specific outputs are expected to include, but are not limited to, a summary of existing literature, analysis of existing data, a sampling and analysis plan, the project dataset, and a technical report with detailed results for all tasks.

Capacity to Address with Mesocosms

Carp manipulations in mesocosms comparing gradients of density from recent historic to control along with, potentially, primary production manipulation, would help quantify the density dependent effects of carp on zooplankton biomass and size structure.

4.2.14 Carp effects on macrophytes

Problem statement

Through physical disturbance and increases in turbidity, carp have contributed to decreases in macrophyte cover in Utah Lake. Reducing the carp population is anticipated to aid in the recovery of submerged aquatic vegetation, but the specific impacts have not been fully quantified. For instance, carp removal has occurred concurrently with drought and subsequent lake level reductions (Landom et al. 2019), which are covered in section 4.2.6. Quantifying the specific effects of carp on macrophyte growth and survival as part of experimental efforts will inform macrophyte re-establishment efforts in Utah Lake.

Existing Data and Information

Landom et al (2019) surveyed macrophyte communities across Utah Lake, noting that lake level fluctuations were primarily responsible for changes in macrophyte cover. While an increase in macrophyte cover was expected due to carp removal efforts, while lower lake levels resulted in decreases in macrophyte cover. Additional mesocosm studies have addressed the effects of carp on macrophytes and invertebrates (Miller and Crowl 2006, Miller and Provenza 2007).

Study Objectives

1. Identify the mechanisms and magnitudes by which carp impact macrophyte communities
2. Distinguish the impacts of carp from concurrent changes in Utah Lake, including lake level

Expected Outputs and Outcomes

A literature review will address the state of understanding of the impacts of carp on macrophytes in Utah Lake and expose gaps in knowledge. Follow-up observational and/or experimental study will fill those gaps. Outcomes of this study will inform the long-term expectations for macrophyte recovery. Specific outputs are expected to include, but are not limited to, a summary of existing literature, analysis of existing data, a sampling and analysis plan, the project dataset, and a technical report with detailed results for all tasks.

Capacity to Address with Mesocosms

Carp manipulations in mesocosms comparing gradients of density from recent historic to control along with macrophyte introduction would help quantify the density dependent effects of carp on macrophyte growth.

4.2.15 Toxin Production and N Species

Note: this topic is covered in section 4.2.10.

4.2.16 Recreational surveys

Problem statement

DWQ and the SP may consider implementing a user perception survey to identify what Utah Lake recreational users consider to be “offensive”, a “nuisance”, or “undesirable” levels of algal biomass, phytoplankton composition, or taste and odor levels. Such endpoints could also be modeled as a function of TN and TP and used to set limits. Advantages of user perception surveys include their scientific rigor and direct linkage to recreational beneficial uses. Disadvantages include the effort in time and resources to conduct such rigorous surveys. Utah has experience conducting these types of surveys (DWQ 2013, Nelson et al. 2015).

Existing Data and Information

Note: It is anticipated that the Steering Committee will pursue this study.

Study Objectives

Note: It is anticipated that the Steering Committee will pursue this study.

Expected Outputs and Outcomes

Note: It is anticipated that the Steering Committee will pursue this study.

Capacity to Address with Mesocosms

This project is not well-suited for a mesocosm study as it relies on community survey information.

4.2.17 Macrophyte role (to biogeochemistry)

Problem statement

Macrophytes have the capacity to alter the biogeochemistry of aquatic systems through uptake and recycling of nutrients, changes in dissolved oxygen and pH as a function of photosynthesis, and reduction of sediment resuspension. Macrophyte re-establishment is a restoration goal for Utah Lake, but the magnitudes of expected changes in biogeochemistry in response to increased macrophyte coverage are unknown.

Existing Data and Information

Preliminary analysis by Tetra Tech indicates that the presence of macrophytes will reduce the incidence of wind-induced sediment resuspension events. We are unaware of any specific studies in Utah Lake that address the nutrient cycling effects of macrophytes.

Study Objectives

1. Characterize the rates of biogeochemical processes associated with macrophytes
2. Predict the effects of macrophyte restoration on Utah Lake nutrient cycles

Expected Outputs and Outcomes

A literature review will address the state of understanding of the impacts of macrophytes on the biogeochemistry of Utah Lake and expose gaps in knowledge. Follow-up observational and/or experimental study will fill those gaps. Outcomes of this study will inform the long-term expectations for macrophyte recovery. Specific outputs are expected to include, but are not limited to, a summary of existing literature, analysis of existing data, a sampling and analysis plan, the project dataset, and a technical report with detailed results for all tasks.

Capacity to Address with Mesocosms

This study would be well-suited for a mesocosm experiment, as it would allow for a range of macrophyte coverage as part of the experimental design, and detailed biogeochemical characterization.

4.2.18 Additional atmospheric deposition data

Problem statement

Atmospheric deposition represents a source of nutrients to Utah Lake, and the magnitude and timing of this deposition is necessary to produce the nutrient budget for the lake. There have been estimates of atmospheric deposition of N and P in published literature (Olsen et al. 2018) and in preliminary observational studies. Additional measurements of atmospheric nutrient loads to Utah Lake will enable evaluation of possible contamination and deposition occurring away from the lake shore. Accurate estimates of atmospheric deposition are needed to resolve the EFDC-WASP and mass balance models for Utah Lake.

Existing Data and Information

Olsen et al. (2018) measured atmospheric deposition at shoreline sites, producing whole-lake estimates based on interpolation of these values for both uncontaminated and contaminated samples. A white paper synthesizing regionally relevant estimates of atmospheric deposition was also developed by Brahney (2019). Additional observational studies are being planned by the Wasatch Front Water Quality Monitoring Council for implementation to overcome methodological concerns associated with Olsen et al. (2018) and to provide additional estimates of atmospheric deposition.

Study Objectives

1. Quantify the atmospheric deposition of N and P to Utah Lake

Expected Outputs and Outcomes

Note: see documentation from Wasatch Front Water Quality Council's Atmospheric Deposition Study

Capacity to Address with Mesocosms

This study involves atmospheric samplers and is not appropriate for a mesocosm study.

4.2.19 Alternative models (PCLake – cyano/macrophyte state change)

Problem statement

The Utah Lake Water Quality Study is in the process of modeling lake processes using EFDC-WASP. Additional process-based lake models (e.g., PCLake) offer the possibility of characterizing additional processes including phytoplankton community structure and state changes in the primary producer community. Incorporating functionality of these models into WASP or enabling these modules to interact with WASP may result in increased accuracy and functionality of the Utah Lake model.

Existing Data and Information

Su and von Stackelberg (2020) have produced a draft report on the application of EFDC-WASP to Utah Lake, which includes a summary of model inputs, sensitivity analysis, model calibration and validation, and uncertainty analysis.

Study Objectives

1. Evaluate the pros and cons of various process-based model structures for characterizing water quality in Utah Lake
2. Evaluate the needed changes to the Utah Lake EFDC-WASP model application
3. Incorporate modules and/or functionality of additional lake models into the EFDC-WASP application

Expected Outputs and Outcomes

The outcomes of this study will be a greater mechanistic understanding of the processes at play in Utah Lake as well as an evaluation of the strengths and weaknesses of the EFDC-WASP application. Expected outputs may include a technical report evaluating various models and the results of model application to Utah Lake.

Capacity to Address with Mesocosms

This project is not well-suited for a mesocosm study as it takes place in a simulation model setting.

5.0 LITERATURE CITED

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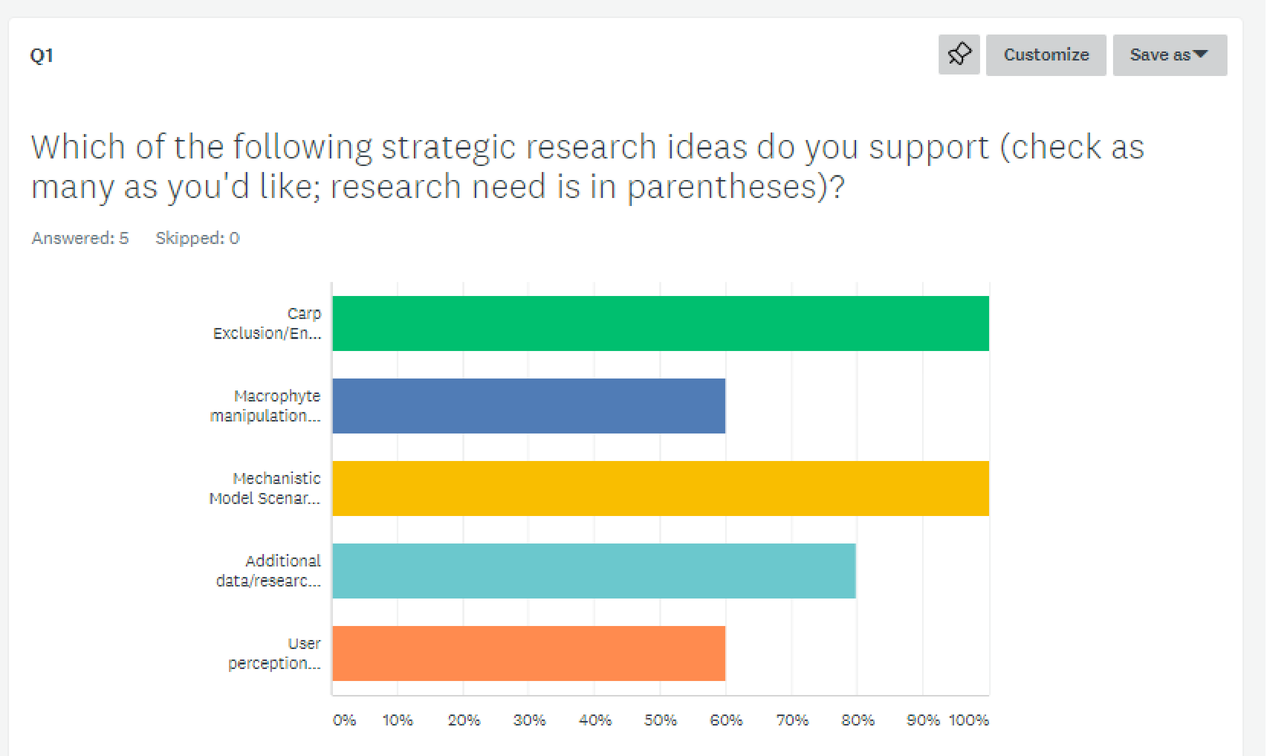
APPENDIX: RESEARCH NEEDS SURVEY RESULTS

We sent a survey to SP members to gauges their initial responses to some high-level research needs and to solicit initial additional strategic research ideas prior to our one-to-one conversations. Five respondents addressed the questions in the survey sent to SP members. These results are summarized here.

Most respondents supported the carp exclosure/enclosure study idea, as well as mechanistic modeling scenarios to study nutrient regimes without human sources and whether such reductions would support phase shift (open to macrophyte dominated) and whether reductions would reduce HABs if an open water stable state is maintained.



Q1

Which of the following strategic research ideas do you support (check as many as you'd like; research need is in parentheses)?

Answered: 5   Skipped: 0

Additional ideas proffered by respondents included:

- Establish nutrient (N and P) budget, including key fluxes modulating budget (e.g., N2 fixation, denitrification)
- Develop cyanobacterial nutrient-bloom thresholds
- Determine seasonal patterns in cyanobacterial toxicity
- In situ limnocorrals/mesocosms that interface with sediment. Nutrient addition/dilution experiments at appropriate spatial and temporal scale and replication to test hypothesis that P, especially reduction of inputs, will reduce frequency and magnitude of cyanoHABS
- Characterization of the impacts of calcite and iron on the availability and mobility of nutrients in the water column and sediments (Charge question 2.3.C: "What is the role of calcite "scavenging" in the P cycle?" high priority; note to be useful this must include an analysis of factors impacting the scavenging and a recommendation/methodology on how to incorporate this impact in mechanistic modeling)
- Characterization of seiche and impacts on lake sediment and nutrient cycling. Increase number/location of water surface elevation gages (presently not sufficient to identify/characterize a seiche; impact on nutrient, macrophytes; support of mechanistic model)

- Field/lab characterization of sediment POM and pore water concentrations (multiple locations; to support application of sediment diagenesis model; a component of the EFDC/WASP model).
- Exploration of supporting mechanistic tools intermediate in complexity to mass balance and EFDC/WASP model (e.g. a 1-box WASP model or Lake2K and a standalone diagenesis model' used to evaluate data and support criteria development)
- Equilibrium P concentrations and pH values observed in Utah Lake (2.4.i and 2.3.v.) [if this is not answered by 2019 research]
- Literature review regarding the inhospitality of the high pH and dissolved oxygen concentrations during algal blooms (Utah Lake exceeds the 110% total gas supersaturation level and is most likely a tough place to be a small fish)
- After seeing the 2019 research results, I expect to have better suggestions for 2020 research needs.
- What is the role of calcite scavenging on the P cycle?
- What is the effect of algal and mineral turbidity on primary production?
- In situ nutrient release (i.e., sediment flux chambers) to complement lab experiments
- Does the lake experience anoxic conditions at the sediment-water interface? If so, does this affect nutrient releases?
- Atmospheric nutrient deposition. Is P in atmospheric deposition "bioavailable"?