UTAH LAKE NUTRIENT MODEL SELECTION REPORT

Algal Bloom in Provo Bay, October 2014

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UTAH DEPARTMENT *of* ENVIRONMENTAL QUALITY
WATER QUALITY

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BACKGROUND

Utah Lake is a highly productive lake that experiences extensive algal blooms in the late summer and fall (Psomas and SWCA, 2007). Utah Lake is considered hypereutrophic according to the trophic state index. Hypereutrophic lakes are very nutrient rich and can be characterized by frequent and severe nuisance algal blooms and low transparency. General concerns associated with elevated nutrient concentrations include the growth of nuisance phytoplankton and periphyton, low dissolved oxygen, elevated pH, and the potential for cyanotoxin production by cyanobacteria (blue-green algae).

Utah Lake was listed on Utah's 2004 §303(d) list for exceedances of state criteria for total phosphorus (TP) and total dissolved solids (TDS) concentrations. The Utah Division of Water Quality (UDWQ) initiated a TMDL study in 2004, and a validation and evaluation report (Psomas, 2005) and pollutant loading and impairment assessment report (Psomas and SWCA, 2007) were completed. Action on the TMDL was subsequently suspended for several reasons, including inability to identify an appropriate water quality endpoint and to allow the effort to remove invasive carp by the Division of Wildlife Resources to proceed and take effect. The difficulty in identifying a water quality endpoint was tied to the lack of data and appropriate modeling tools for the shallow Utah Lake system.

Levels of microcystins, a neurotoxin associated with blue-green algae, in water samples collected from an algal bloom along Lindon Marina in October 2014 exceeded health advisory levels established by the Environmental Protection Agency (EPA) and World Health Organization (WHO). The elevated concentrations of cyanotoxins are potentially harmful with severe health consequences in case the water is ingested by human and or animal, and were implicated in the death of a dog that had ingested the water (Bittner, 2014). Subsequently, DWQ is investing more resources in understanding the nutrient related issues in Utah Lake in support of restarting the TMDL process in the future.

Principles of lake ecology suggest that shallow lakes, defined as having a maximum depth less than 20 feet and an average depth less than 10 feet, exist in one of two alternate stable states: a clear water state and turbid water state (Scheffer 1998). The clear water state is dominated by rooted aquatic plants (macrophytes) that limit bottom sediment resuspension and phosphorus recycling. The turbid state is dominated by planktonic algae and suspended inorganic sediments that reduce water clarity and limit rooted aquatic vegetation growth. Typical of the turbid state are high densities of carp that consume benthic vegetation and disturb sediments. Generally, there are no intermediate stable states of existence for shallow lakes. Whether Utah Lake historically ever was in a macrophyte dominated clear state is an open question that is currently being studied by various researchers.

The UDWQ is evaluating nutrient related issues in Utah Lake (DWQ 2016). One component of the work plan is the development of a nutrient model for Utah Lake to support study objectives and nutrient management of the lake. This report presents the model objectives, reviews the important lake processes related to eutrophication, evaluates the potential lake modelling programs, and recommends a model for use on Utah Lake.

Model Objectives

The primary objective is to develop a water quality management tool to address eutrophication in Utah Lake. Following are the key objectives for the Utah Lake nutrient model:

1. Develop a decision support tool for Utah Lake, including the relationship of phosphorus and nitrogen to water quality endpoints such as DO, pH, and nuisance and harmful algal blooms, as well as export of TP, TN and organic matter to the Jordan River.
2. Improve understanding of the nutrient dynamics in Utah Lake and the formation of nuisance and harmful algal blooms (cyanobacteria).
3. Predict effects of various nutrient loading scenarios on formation of nuisance and harmful algal blooms.
4. Predict transition from turbid state to clear state, and vice versa.

A secondary objective of the nutrient model is to identify input and calibration data gaps and support planning of data collection efforts.

In order to ensure that the model is appropriate to apply as a decision support tool for environmental regulation, the model developer should follow the data quality objectives (DQO) process as outlined in *Guidance on Systematic Planning Using the Data Quality Objectives Process* (EPA 2006) for the acquisition of environmental data and preparation of a modeling quality assurance project plan (QAPP). Other aspects to consider include stakeholder buy-in, peer review, and model uncertainty. In *Guidance on the Development, Evaluation, and Application of Environmental Models* (EPA 2009), the Environmental Protection Agency's Council for Regulatory Environmental Modeling recommends that model developers and users:

> *(a) subject their model to credible, objective peer review;*
>
> *(b) assess the quality of the data they use;*
>
> *(c) corroborate their model by evaluating the degree to which it corresponds to the system being modeled; and*
>
> *(d) perform sensitivity and uncertainty analyses. Sensitivity analysis evaluates the effect of changes in input values or assumptions on a model's results. Uncertainty analysis investigates the effects of lack of knowledge and other potential sources of error in the model (e.g., the "uncertainty" associated with model parameter values). When conducted in combination, sensitivity and uncertainty analysis allow model users to be more informed about the confidence that can be placed in model results. A model's quality to support a decision becomes better known when information is available to assess these factors.*

Previous Studies

A literature review up to 2005 is presented in the Task 1 Technical Memorandum for the Utah Lake TMDL (Psomas, 2005). The literature review will be updated as part of the water quality study. Below are reviews of more recent studies of particular relevance to developing a Utah Lake nutrient model.

Callister (2008), under the direction of Dr. Robert Spall, evaluated circulation patterns in Utah Lake by building a model in ELCOM, a 3-D hydrodynamic model developed and maintained at Western Australia University. The findings of the study were that the circulation and current patterns in the lake are highly dependent on wind speed and direction, with minimal effect from river inflow and outflow. Circulation patterns in Goshen Bay and Provo Bay were found to be independent of the open waters of the lake.

Researchers at Brigham Young University have developed the Utah Lake Water Quality Salinity Model (LKSIM), which simulates water balance and salt ion concentrations in Utah Lake. Rice (1999) updated and calibrated the model to water years 1930-1998. More recently, the model was updated again to reflect more recent tributary flow and loading data (Marelli 2010, Dye 2012, Liljenquist 2012).

Hogsett and Goel (2013) found that sediment phosphorus was primarily bound to calcium, with a mean sediment content of 900 mg P/kg dry sediment. Phosphorus release from the sediments was observed at four sites, but at a lower rate than ambient concentration. Phosphorus release was increased by lowering the ambient pH. Sediment oxygen demand (SOD) varied from -1.0 g O_2/m^2/day midlake to -1.5 g O_2/m^2/day near shore.

Lake Processes to be Modeled

The following sections discuss key physical, chemical and biological processes in Utah Lake relevant to nutrient dynamics and eutrophication.

Physical Characteristics

Mixing

The mechanism and the degree to which water flows and constituents are mixed within Utah Lake is a key consideration in selecting the appropriate model.

Due to the shallow nature of the lake, and the combination of the effect of wind and shear forces along the lake bottom, Utah Lake is widely considered to be fully mixed through its entire depth. The lack of stratification in the lake will allow for a simplification of the vertical dimension.

Lateral mixing between and within the bays and the open water of the lake is more complex and less well understood than the vertical mixing. Based on the conclusions of Callister (2008), the lateral mixing is highly dependent on wind speed and direction, and the circulation patterns in the open water and bays are independent.

Based on a wind rose constructed using ten years of data (2005-2015) from the weather station at Provo International Airport (KPVU), the predominant wind direction is from the South-Southeast-East for approximately 40% of the time during the entire year (Figure 1) and approximately 50% of the time during the summer critical season (Figure 2). However, winds of higher magnitude do occur from the Northeast for a significant portion of time as well.

This analysis indicates that the dominant current direction in Utah Lake is generally South to North towards the outlet to the Jordan River. Therefore, representing flow in one direction between lake segments of uniform water quality could be adequate for the purposes of representing water flow and mixing in the model. An example model segmentation showing direction in one direction between fully mixed lake segments is shown in Figure 3.

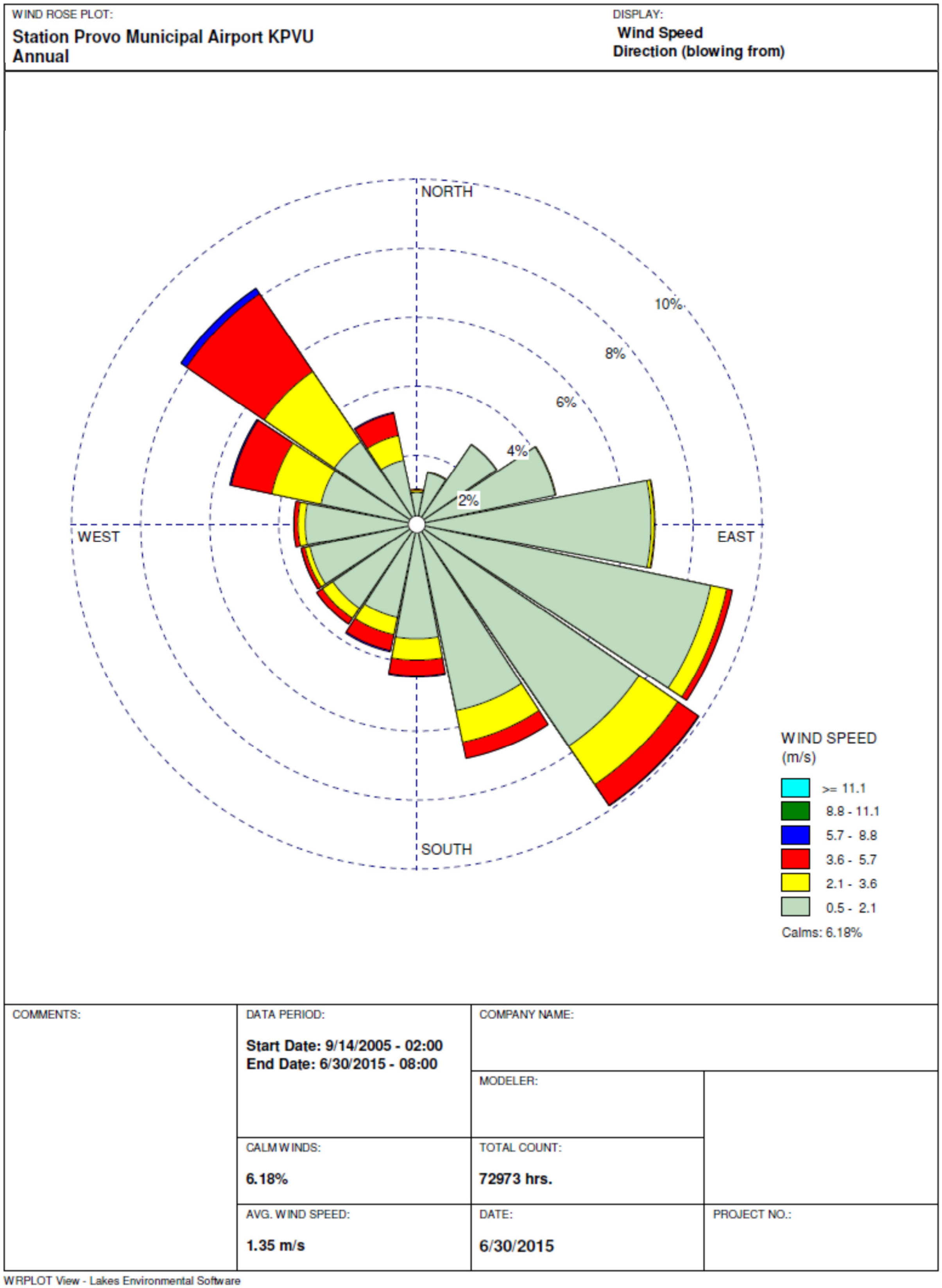

Figure 1: Wind rose Provo International Airport using year round data

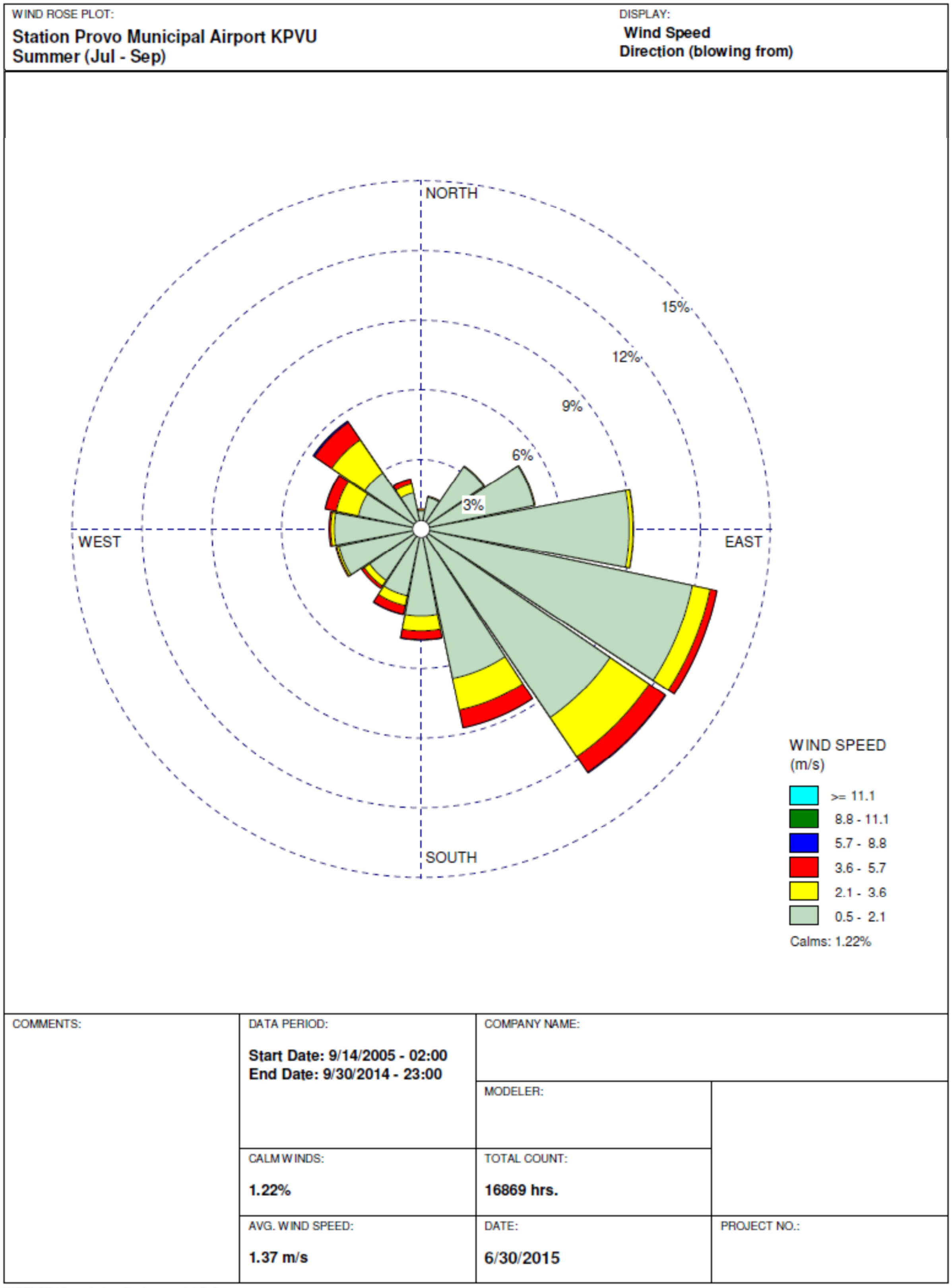

Figure 2: Wind rose from Provo International Airport using summer data only (July – September)

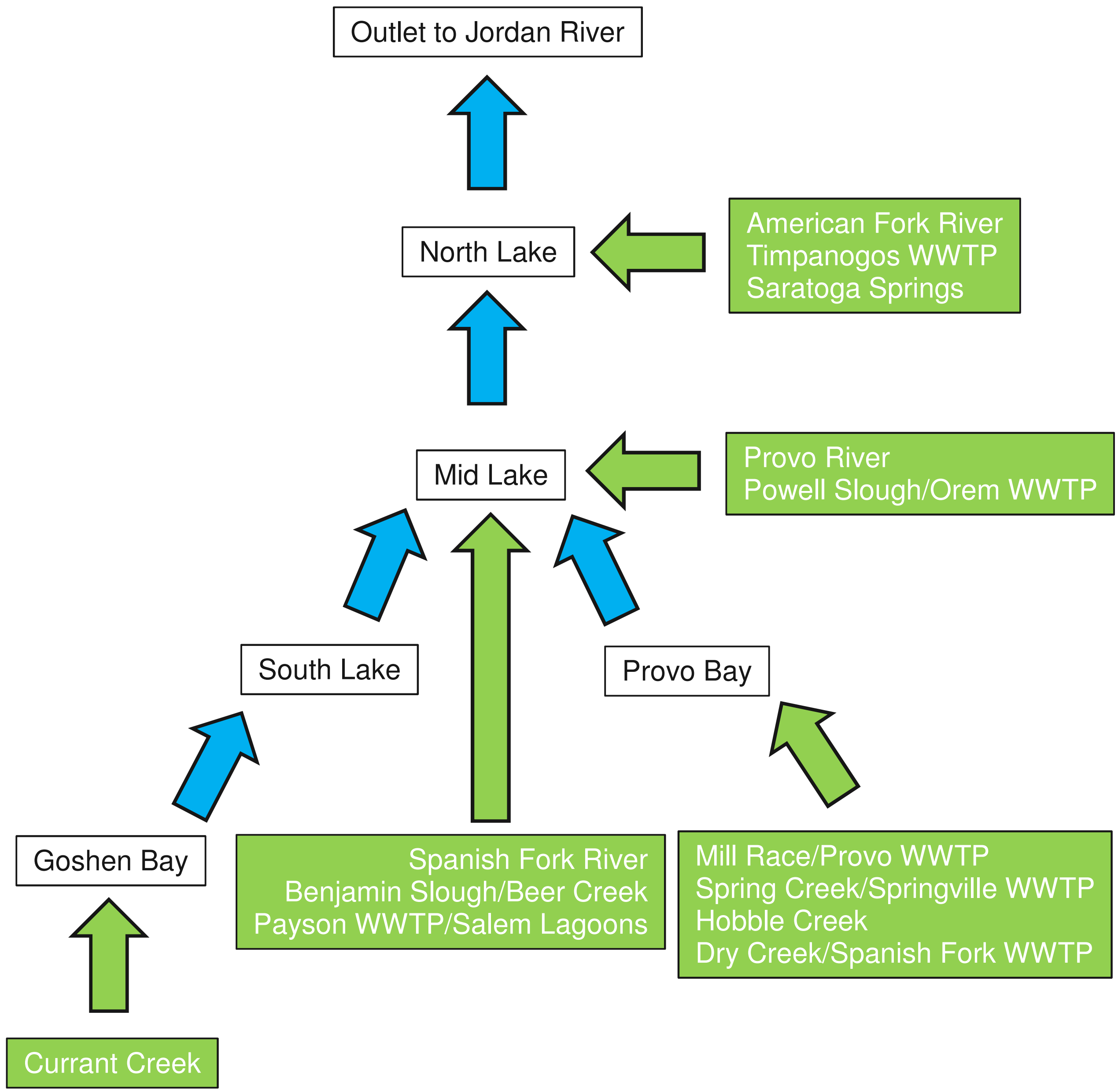

Figure 3: Example model segmentation showing flow in one direction

SEDIMENT RESUSPENSION

An important process in shallow lakes is the settling and resuspension of sediments. Suspended sediments affect the water clarity of the lake, which can reduce plant growth. In addition, phosphorus bound to inorganic minerals may desorb, elevating phosphorus concentrations in the water column.

Resuspension of sediments in shallow lakes results from both wind and wave action and the feeding behavior of benthivorous fish. The presence of macrophytes has been shown to decrease the resuspension of sediments. In many cases, a three-dimensional (3-D) hydrodynamic model is required to account for the localized effects of wind and wave action. An example model grid for a 3-D hydrodynamic model is shown in Figure 4.

TEMPERATURE AND ICE COVER

Temperature is an important property of the lake environment that affects the kinetic rates of biological and chemical processes. The model must be able to simulate temperature dynamics, including surface and bottom heat exchange.

Typically, Utah Lake is frozen for several months each winter. Ice formation can affect the heat balance, mixing characteristics, and water quality in lakes and reservoirs. Ice cover shields the underlying water against wind induced mixing. Ice cover also retards light penetration and surface reaeration.

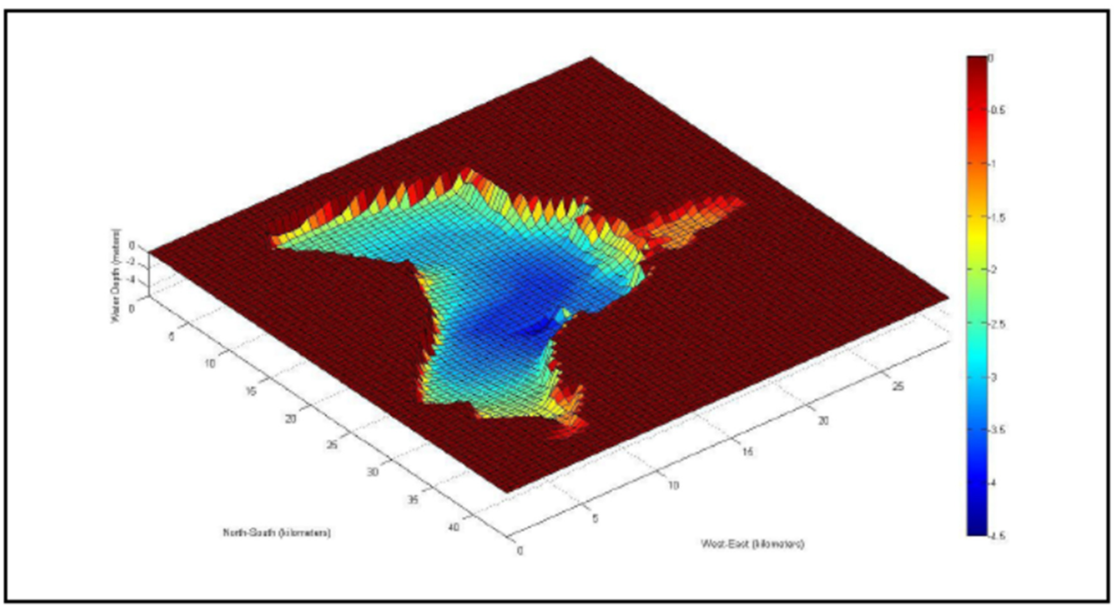

Figure 4: Example of 500 meter model grid of Utah Lake (Source: Callister 2008)

INTERNAL NUTRIENT DYNAMICS

The nutrient dynamics and transformations within Utah Lake are critical processes that must be represented in the model in order to predict the effects of various nutrient loading scenarios. The typical key nutrients in lake models are phosphorus, nitrogen and silica.

PHOSPHORUS

Phosphorus (P) is a conservative element that remains in Utah Lake unless it is exported through the outlet to the Jordan River or harvested as plant and fish biomass. As such, phosphorus has accumulated in the lake from decades of P loading from the tributary watershed and point sources. The key phosphorus dynamics are shown in Figure 5. Phosphorus can be found in an inorganic, readily bioavailable form (referred to as ortho-phosphate or PO4) or bound in an organic form (OP), either in a dissolved or particulate state. Due to its negative charge, PO4 in the dissolved state can adsorb to mineral particles, such as calcium carbonate ($CaCO_3$), that settle to the lake bottom. The partition of phosphorus between the aqueous state and sediment-bound state is dependent upon the mineral (i.e. calcium, magnesium, iron, or aluminum) and the pH of the water. Hogsett and Goel (2013) found that sediment-bound inorganic phosphorus was released by lowering the ambient pH, and could be mediated by bacteria, particularly in organically rich sediments.

An important consideration in the model, beyond the ability to simulate the sorption of PO4 to minerals, is quantifying the PO4 in the lake bottom sediments that would be available for release and uptake by algae. This legacy pool of phosphorus will be critical in evaluating the potential for a hysteretic response to reducing the phosphorus load to the lake. As far as the transition from the inorganic to the organic form and vice versa, the model will need to simulate plant uptake of PO4 during photosynthesis and release of PO4 after death and decomposition. An important consideration is the decomposition of organic matter in the sediments through diagenesis.

Another important factor in the phosphorus balance in the lake is P uptake by secondary producers such as zooplankton, benthic macroinvertebrates and benthivorous fish (carp) and release after death. The amount of carp harvested from the lake as part of the June Sucker Recovery Implementation Project's carp removal program needs to be quantified and incorporated into the model, as well.

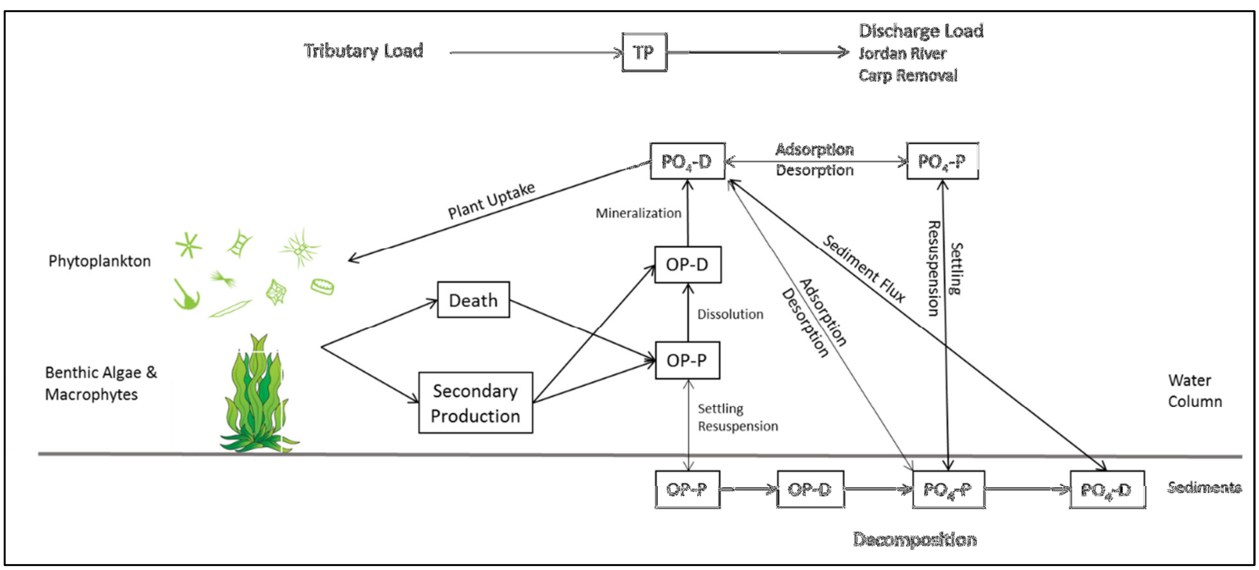

Figure 5: Simplified representation of phosphorus dynamics in Utah Lake

NITROGEN

Nitrogen (N) is an element found in the gas, liquid and solid phase that can enter and exit the lake through multiple pathways. The key processes in the aquatic nitrogen cycle are shown in Figure 6. Important dynamics to highlight relative to Utah Lake are the plant uptake of ammonium (NH4) and nitrate/nitrite (NO3), as well as nitrogen fixation (N2) by some algal species. Equally important is the return of organic nitrogen to NH4 by secondary producers during plant decomposition.

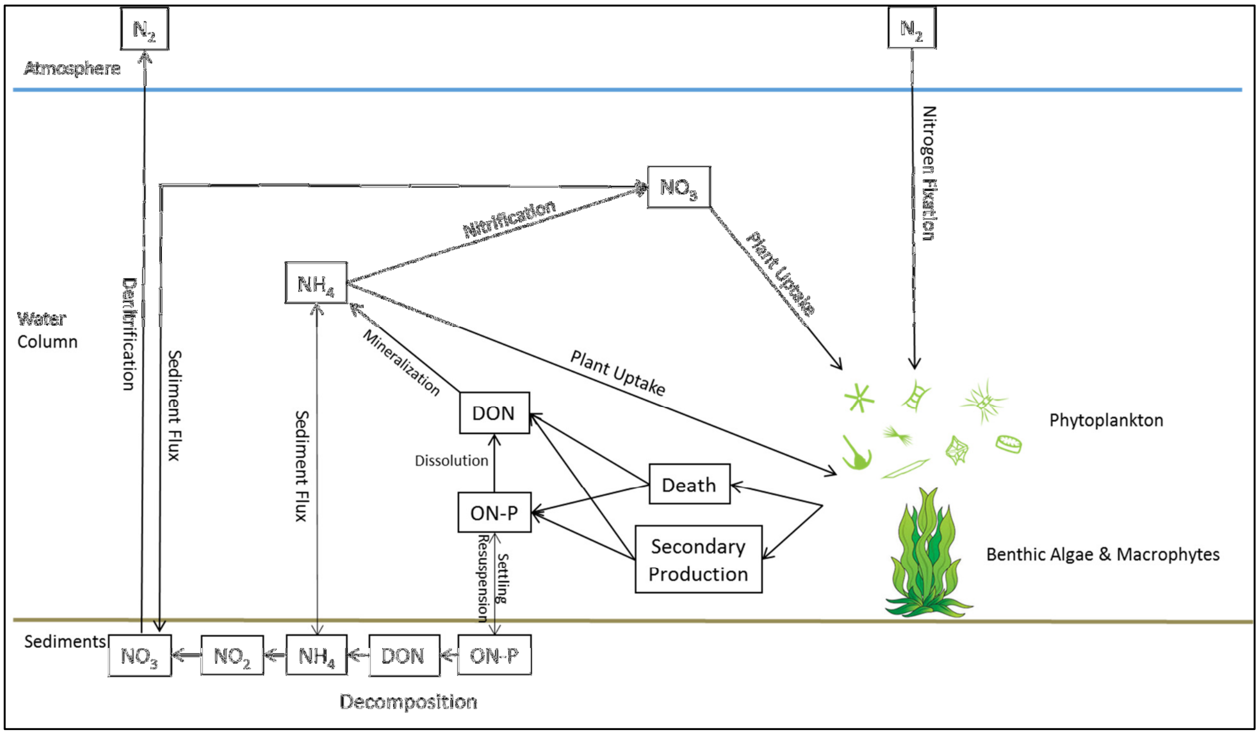

Figure 6: Simplified representation of nitrogen dynamics in Utah Lake

SILICA

Silica, or silicon dioxide ($SiSO_2$), is a chemical compound that has been found to be the limiting nutrient in the growth of diatoms in some freshwater and marine systems. No previous studies were found that evaluated whether silica plays a critical role in diatom growth in Utah Lake. Silica oxides comprised 9.1% to 52.1% of lake sediments by mass in 13 samples collected by Hogsett and Goel (2013), indicating an abundance of silica in the lake environment.

EUTROPHICATION

Eutrophication is excessive richness of nutrients in a lake that causes a dense growth of plant life. Some of the environmental issues that can result from eutrophication are discussed in the sections below.

ALGAL BLOOM FORMATION

A key objective of the model is to predict the formation of nuisance algal blooms (NAB) and harmful algal blooms (HAB). Nuisance algal blooms are unsightly and impede recreational use of the water, but are not directly toxic to aquatic life or humans. The growth of NABs can result in elevated pH and the death and decomposition of NABs, can result in low dissolved oxygen in the water column that is toxic to aquatic life. Harmful algal blooms contain cyanobacteria (blue-green algae) that may produce toxins that harm aquatic life, animals and/or humans.

In order to predict the formation of NABs and HABs, the model must be able to distinguish between phytoplankton species such as diatoms, green algae, and blue-green algae, and the environmental conditions under which each has a competitive advantage. An example of the seasonal abundance and succession of phytoplankton species is shown in Figure 7.

An important consideration for HABs is the environmental conditions and mechanisms which result in the production of toxins by the blue-green algae. HABs are typically extreme events characterized by high spatial (days to weeks) and temporal (localized) variability that are generally beyond the resolution of the predictive capabilities of the available data and models (Bierman et al. 2013). Therefore, the environmental conditions and mechanism that trigger HABs in Utah Lake requires further research and a probabilistic correlation between the presence of blue-green algae and formation of HABs needs to be developed to support the interpretation of the model output.

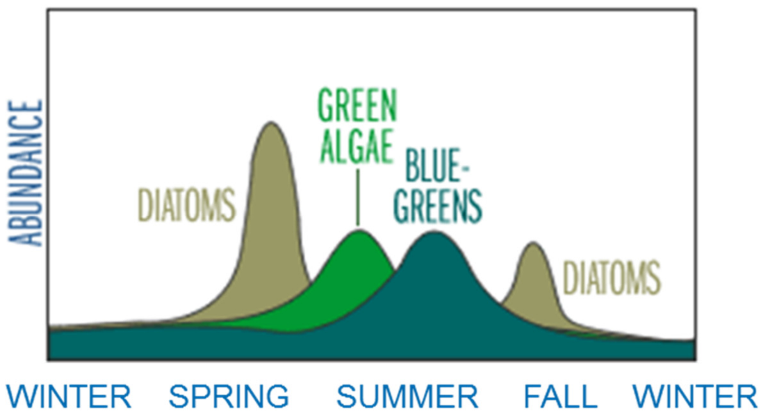

Figure 7: Example of seasonal succession of phytoplankton populations in a lake environment

DISSOLVED OXYGEN

As described previously, the death and decomposition of NABs can result in low dissolved oxygen (DO) levels that are toxic to aquatic life. In addition, the diel fluctuation in DO resulting from photosynthesis and respiration of plant life can result in excursions of minimum DO criteria.

In order to accurately predict DO levels in the lake, the model will need to represent the sources and sinks of DO including: reaeration due to atmospheric exchange and wind, nitrification, photosynthesis, respiration, and organic matter decomposition in the water column and sediments.

In order to simulate diel fluctuation of DO, the model would need to be run at a sub-daily time step, i.e. hourly, which requires high resolution meteorological, hydrological and water quality input data.

Although limited continuous DO data has been collected from Utah Lake, it appears that low DO is generally not a concern in the open waters of the lake, whereas excursions have occurred in Provo Bay at times. This needs to be verified with additional continuous DO data.

Sediment Diagenesis

Sediment diagenesis refers to the decomposition and mineralization of organic materials in the lake bottom, which results in a sediment oxygen demand (SOD) and nutrient releases. After Di Toro (2001), the typical formulation for this process in water quality models represents the sediments as two well-mixed layers: a thin aerobic layer (approximately 10 cm) overlying a thicker anaerobic layer (Figure 7). The major processes involved include: fluxes of particulate organic matter and inorganic nitrogen, phosphorus and carbon between sediment layers and to/from the water column, and mineralization of the organic matter. Often the decomposition of organic matter is divided into three classes: a labile class that decomposes in hours or days, a refractory class that decomposes in months or years, and a relatively inert form that decomposes in decades (G1, G2 and G3 in Figure 8).

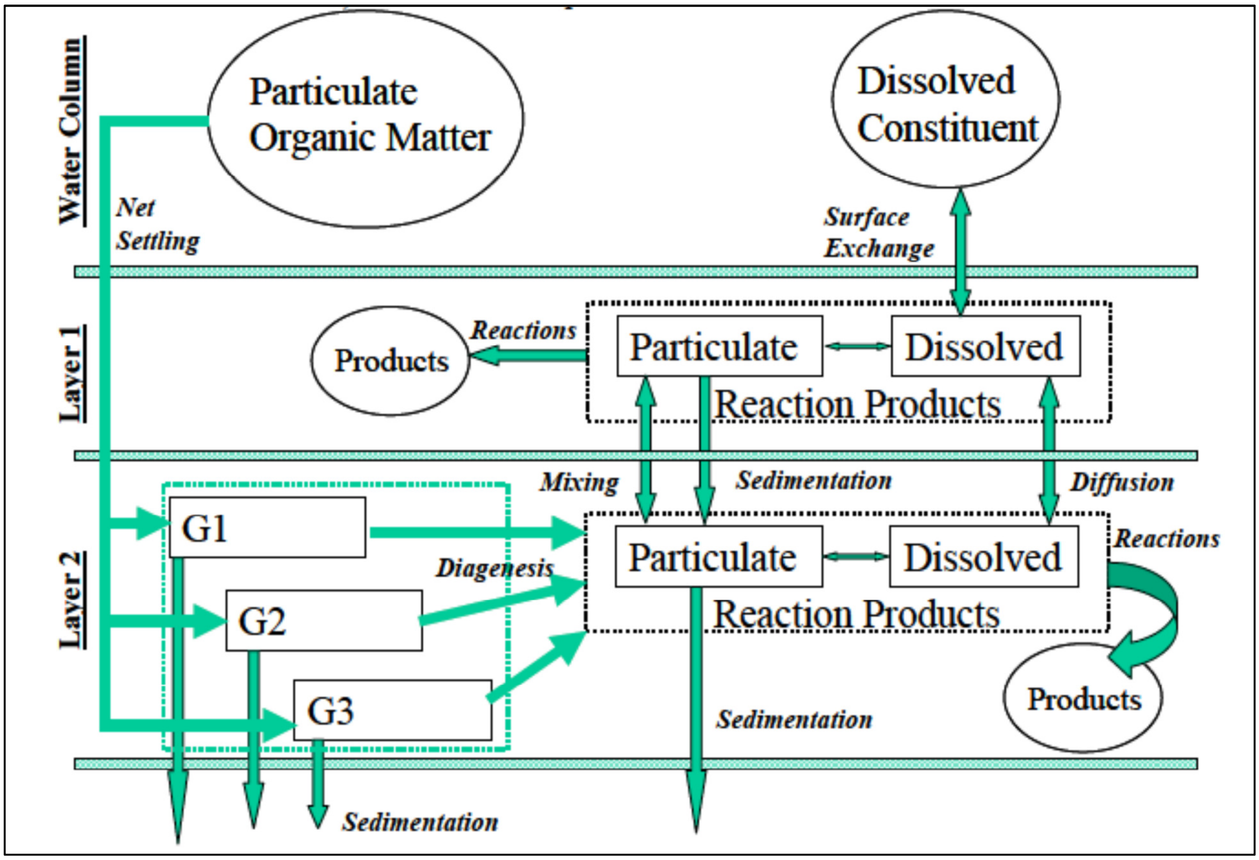

Figure 8: Conceptual model for sediment diagenesis (Source: Martin and Wool 2012)

pH

Growth of plant life can also result in elevated pH levels in the water column that exceed water quality criteria to protect aquatic life use. The model would need to track inorganic forms of carbon, such as carbon dioxide (CO_2) and dissolved inorganic carbon (DIC), in order to simulate pH.

Elevated pH may be of concern both in the open waters of Utah Lake and in Provo Bay. This needs to be verified with grab sample and continuous pH data.

Since pH also plays a critical role in the adsorption and desorption of phosphorus to particulate minerals, pH dynamics is considered an important process to represent in the model.

Shallow Lake Alternate Stable States

Predicting the transition from the phytoplankton dominated turbid state to the macrophyte dominated clear state, and vice versa, is an objective of the model that will require simulation of the aquatic food web as well as the geochemistry of the lake.

Evidence suggests that periphyton plays a significant role in the shift in shallow lakes from one state to the other (Phillips et al. 1978). Two factors that regulate periphyton biomass have been researched extensively in the literature: bottom-up control by nutrients and top-down control by grazers. Bottom-up control results from excess nutrient loading to the lake that tends to favor algal growth (free floating phytoplankton and attached periphyton) over macrophyte growth because algae obtain nutrients primarily from the water column. The enhanced algal production exceeds the grazing pressure from zooplankton and macroinvertebrates, which results in higher turbidity in the water column that limits light to the macrophytes. A feedback mechanism is that the reduced presence of macrophytes results in increased sediment resuspension and higher turbidity. Top-down control results from a bioturbation of the ecosystem, such as the introduction of benthivorous fish (carp), which causes higher predation on zooplankton and macroinvertebrates. The resultant reduction in grazing pressure on periphyton gives the algae a competitive advantage over the macrophytes. A feedback mechanism is that the benthivorous fish tend to stir-up bottom sediments through their feeding action, leading to higher turbidity and reduced light. Typically, both bottom-up and top-down forces and their interaction factor into the periphyton biomass in aquatic ecosystems (Hillebrand 2002).

Following is a discussion of the key mechanisms that contribute to the alternate stable states of shallow lakes.

Water Clarity

Water clarity plays an important role in the emergence and establishment of macrophytes under the clear water stable state. The amount of light that reaches the bottom of the lake is affected both by the growth and abundance of phytoplankton and the amount of suspended sediments in the water column. An important consideration in predicting suspended sediments are the processes of settling and resuspension. Resuspension in shallow lakes has been attributed to both wind and wave action, and the feeding behavior of benthivorous fish. The presence of macrophytes has been shown to decrease the resuspension of sediments. These mechanisms will need to be well understood in order to evaluate the potential for the establishment of macrophytes.

An analysis of in-lake samples collected from 2009-2012 showed that the composition of the total suspended solids (TSS) was on average mostly inorganic material (~75%) versus organic material (~25%). The ratio of inorganic solids to organic solids was consistent when evaluating only those samples where the volatile suspended solids (VSS) were above method reporting limits and when evaluating all samples assuming VSS at the reporting limit for samples below detection. VSS is a measure of organic concentration that includes both dead detrital material and living plankton.

Periphyton

As discussed above, periphyton has been theorized to play a key role in the switch of alternate stable states in shallow lakes. Periphyton are algae that are attached to the substrate and get their nutrients primarily from the water column. Macroinvertebrates graze on periphyton and act as a regulating force on the total biomass of attached algae.

Macrophytes

In order to accurately predict conditions under the clear water state, the model will need to be able to simulate macrophyte emergence and growth. From a modeling perspective, macrophytes are distinct from phytoplankton and periphyton in several key ways. Macrophytes acquire the nutrients necessary to support growth from the sediments as well as the water column. The light used for photosynthesis varies through the water column and is reduced by shading from the plant. In addition, the consumption of macrophytes by benthic macroinvertebrates, carp and other benthivorous fish are different from the secondary producers that graze on phytoplankton and periphyton.

Secondary Producers

How secondary production of zooplankton, benthic macroinvertebrates, and carp impact nutrients, algal growth and macrophyte establishment is an important consideration in predicting the switch of alternate stable states. Evaluating the recovery potential of the native June Sucker fishery is not a primary objective of the model, but prediction of the stable state of the lake could assist with this effort.

Priority

Ideally the selected model would represent all of these processes, but it is acknowledged that there are trade-offs to how well each model performs at each of these functions. Based on the primary objectives of the nutrient model and the primary water quality concerns for Utah Lake, predicting the nutrient dynamics and algal growth are higher priority than responses of dissolved oxygen, pH and the food web to eutrophication.

MODEL SELECTION

MODEL SELECTION CRITERIA

This section describes the important characteristics that will be used to evaluate and select the model.

- Complexity
  The model should have the appropriate level of complexity while encompassing the necessary components to address the model objectives and questions of concern.

  If the model lacks complexity, key lake processes may be over-simplified or missed entirely, resulting in inaccurate extrapolation. In addition, the model may not address relevant management questions and be insufficiently adaptable to changing management requirements. The model may also not be defensible and credible under review.

  If the model is overly complex, data collection, model parameterization and computational requirements may be significantly increased, which can result in additional model uncertainty. The complexity can result in additional analysis and do-loops, which tends to shift the focus from management solutions.

- Processes
  The model should simulate the relevant physical, biological, and chemical processes and predict the response variables of concern.

- Data Requirements
  The data required to populate and calibrate the model should be readily available or reasonable to collect given time and resource constraints.

- Transparency
  Due to the potential application of the model to regulatory actions, the model must have sufficient transparency that a stakeholder or third party review could be conducted with reasonable effort. Considerations under transparency include: cost of model licensing, relative ease of use, availability of user manual and training materials, size of user base, and access to user forums.

- Flexibility
  The model should be adaptable to changing management requirements and modifiable as understanding of key lake processes improves. In order to be flexible, the model source code needs to be readily available and modifiable.

- Compatibility
  The model should have the ability to interface with existing and proposed models within the watershed, i.e. Jordan River and Great Salt Lake Integrated Water Resources Model.

The models were evaluated and ranked based on their overall ability to meet the selection criteria utilizing best professional judgement.

MODEL SCREENING

A list of potential models was developed for the purposes of screening out a select few for more detailed evaluation. The screening list was primarily based on a review of Shoemaker et al. (2005), Mooij et al. (2010), and Bierman Jr. et al. (2013). Table 1 summarizes the potential models.

The following models were carried forward for more detailed evaluation: WASP, CAEDYM, PCLAKE and CE-QUAL-W2. Based on the model objectives and the complexity of Utah Lake, the BATHTUB model was considered too simple and dropped from further consideration. The water quality models WASP, CAEDYM, and PCLAKE have the ability to be linked to either a 1-dimensional (1-D) or a 3-dimensional (3-D) hydrodynamic model. The preferred linkage depending on model capabilities will be discussed further below. Although Utah Lake is not considered vertically stratified, CE-QUAL-W2 was carried forward since it is the US Bureau of Reclamation's preferred reservoir model and has been widely applied in the Intermountain West and Utah.

Table 1: List of potential models

Model	Dimen-sions*	Description
PCLAKE	0-D	Shallow lake ecosystem model. Program maintained by Netherlands Environmental Assessment Agency and Netherlands Institute of Ecology.
BATHTUB	1-DH	Steady-state, empirical nutrient balance model. Program distributed by United States Army Corps of Engineers..
WASP	1-DH	Water Quality Analysis Simulation Program maintained by EPA.
DYRESM-CAEDYM	1-DV	Linked 1-D hydrodynamic model to water quality model. DYnamic REservoir Simulation Model - Computational Aquatic Ecosystem DYnamics Model. Program maintained by University of Western Australia.
DUFLOW-PCLAKE	1-DH	Linked 1-D hydrodynamic model to shallow lake ecosystem model. DUFLOW program maintained by STOWA.
CE-QUAL-W2	2-DV	Vertically stratified lake. Program maintained by Portland State University.
EFDC-WASP	3-D	Environmental Fluid Dynamics Computation - Water Quality Analysis Simulation. Program maintained by EPA.
ELCOM-CAEDYM	3-D	Estuary, Lake and Coastal Ocean Model - Computational Aquatic Ecosystem DYnamics Model. Program maintained by University of Western Australia.
DELFT3D-ECO	3-D	Linked 3-D hydrodynamic model to ecosystem model. Program maintained by Deltares.
IPH-TRIM3D-PCLAKE	3-D	Linked 3-D hydrodynamic model to shallow lake ecosystem model. Program maintained by Netherlands Environmental Assessment Agency and Netherlands Institute of Ecology.
*: H and V modifiers refer to horizontal and vertical dimension, respectively.		

MODEL REVIEW

A brief description of each of the models on the short list is provided below and model capabilities are summarized in Table 2.

PCLAKE

PCLAKE is an open source and public domain ecosystem modeling tool maintained jointly by the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Institute of Ecology. The model was developed with the objective of simulating eutrophication of shallow lakes and the transition from turbid water state to clear water state, and vice versa, in response to varying nutrient loads.

PCLAKE may be run independently as one waterbody (0-D) or coupled with hydrodynamic model DUFLOW (1-DH) or IPH-TRIM3D (3-D). DUFLOW is a proprietary model available from Deltares that requires a license fee. The program simulates the major biogeochemical processes influencing water quality, including primary production, secondary production, nutrient cycling, oxygen dynamics and the movement of sediment (Janse 2005). PCLAKE has the ability to simulate up to three different phytoplankton groups (diatoms, green algae, cyanobacteria), one zooplankton group, one benthic algae group, one macrophyte group, one macroinvertebrate group, one benthivorous fish group with two life stages (juvenile and adult), and one predatory fish group. PCLAKE does not simulate bird response; however, the effect of bird grazing on vegetation can be incorporated. PCLAKE simulates sediment diagenesis, which predicts sediment oxygen demand and nutrient fluxes from the underlying benthos.

Inorganic carbon (CO_2) is not explicitly modelled. Therefore, the elevation of pH due to algal growth cannot be evaluated using PCLAKE. In addition, the pH dependence of P adsorption to sediments is not simulated; rather P adsorption is simulated based on an adsorption isotherm that defines the relation between dissolved P concentration and the amount of adsorbed P per mass of adsorbent at equilibrium. Sediment resuspension is estimated using an empirical logistic relation between lake depth and seston concentration from a data set of 35 lakes that is corrected for lake fetch. The effect on resuspension of sediments by benthivorous fish and macrophytes is also considered.

PCLAKE has been calibrated to nutrient, transparency, phytoplankton and vegetation data on more than 40 European (mainly Dutch) shallow lakes, which accurately predicted the clear or turbid stable state, and systematic sensitivity and uncertainly analyses have been performed (Janse et al. 2010). In a study of differing shallow lakes, the critical phosphorus loading to switch stable states was found to decrease with lake area, mean lake depth and retention time, and increase with relative marsh area and fishing intensity (Janse et al. 2008). The model has not been widely used outside of Europe, and some documentation and reports are in Dutch.

WASP

WASP is an open source and freeware water quality model maintained by the EPA. WASP simulates nutrients and water quality dynamically in both the water column and the underlying sediments. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model (Wool et al. 2005). WASP can also be linked with hydrodynamic and sediment transport models that provide flows, depths, velocities, temperature, salinity and sediment fluxes. WASP Version 8 has the ability to simulate five different phytoplankton groups, three benthic algae groups, and one zooplankton group. WASP contains a sediment diagenesis model that predicts sediment oxygen demand and nutrient fluxes from the underlying benthos (Martin and Wool 2012).

WASP simulates the settling, accumulation, burial and resuspension of three different inorganic sediment size classes. Resuspension is predicted based on specification of a scour velocity, a formulation that is less suitable for lotic systems where erosion is wind and wave induced. Due to the importance of simulating the resuspension of sediment resulting from wind forces and wave action, it was determined that the 3-D hydrodynamic model EFDC would need to be linked to WASP to adequately capture this process.

The adsorption of P to sediments is simulated based on a partition coefficient that is at instantaneous equilibrium. Improvements to the simulation of phosphorus sorption dynamics, including dependence on pH, would require modifications to the source code.

WASP does not simulate benthic macroinvertebrates, fish or bird response. In order to simulate the food web response, a separate ecological model would need to be developed and linked to WASP, which is referred to as the hybrid model (Bierman Jr. et al. 2013). The linkage of WASP to ecological response indicators has been implemented on previous TMDLs, including the Neuse River (oysters), Lower St. Johns River (DO recruitment), Florida numeric nutrient criteria for estuaries (seagrasses), and Savannah River (fish biogenics) [Tim Wool, personal communication on January 12, 2016].

WASP is one of the most widely used water quality models in the United States that has frequently been applied to the development of Total Maximum Daily Loads (TMDL). WASP models have been applied to all of the major estuaries in Florida to support the development of numeric nutrient criteria. A WASP Version 5 model was developed for shallow Lake Okeechobee and the source code modified to compute sediment resuspension based on wind-wave action and bottom shear stress (James et al. 1997; James et al. 2005). Additional enhancements have since been made to the Lake Okeechobee Water Quality Model (James 2013).

CAEDYM

CAEDYM is a proprietary aquatic ecological model maintained by the Centre for Water Research (CWR) at the University of Western Australia. CAEDYM is programmed in Fortran-90 and runs on Macintosh, Linux, Unix and Windows operating systems, and the source code is made freely available to scientists interested in modifying or developing the code. The cost of the software license is AU$6,000 (~ US$4,375), which includes the latest versions of DYRESM, ELCOM and CAEDYM, and one year of updates.

It may be run independently or coupled with hydrodynamic models DYRESM (1-DV) or ELCOM (3-D). CAEDYM simulates the major biogeochemical processes influencing water quality, including primary production, secondary production, nutrient and metal cycling, and oxygen dynamics and the movement of sediment (Hipsey et al. 2013). CAEDYM has the ability to simulate up to seven different phytoplankton groups, five zooplankton groups, four benthic algae groups, one macrophyte group, three macroinvertebrate groups (bivalves, polychaetes, crustacean grazers), and three fish groups. CAEDYM does not simulate bird response. CAEDYM contains a sediment diagenesis model that predicts sediment oxygen demand and nutrient fluxes from the underlying benthos.

CAEDYM simulates the settling, accumulation, burial and resuspension of six different inorganic sediment size classes as well as labile and refractory particulate organic matter. CAEDYM estimates sediment resuspension for each particle type based on a comparison of critical shear stress to the bottom shear stress due to unidirectional steady currents and oscillatory wave currents.

CAEDYM includes a sophisticated and generic geochemical module which solves for the equilibrium speciation of the solution. The module solves for pH and other solution properties. Optional mineral or gas phases can be simulated, as well. The geochemical module can be used to simulate the adsorption/desorption of P to sediments based on equilibration.

The DYRESM-CAEDYM linked model was also dropped from further consideration, as DYRESM simulates vertical stratification and not horizontal variance.

Since DYRESM simulates vertical stratification and not horizontal advection and diffusion, it was not considered suitable for application to a shallow lake. Therefore, it was determined that the 3-D ELCOM model would need to be linked to CAEDYM.

CAEDYM has been widely applied throughout the world; the limited applications in the United States include Lake Mead in Arizona and Nevada, Lake Elsinore and Canyon Lake in California and Coeur d'Alene Lake in Idaho (Hipsey et al. 2007). A DYRESM-CAEDYM modelling study of a shallow lake in New Zealand found that reducing internal nutrient loading had a greater effect on algal bloom and cyanobacteria formation than reducing external nutrient loading (Burger et al. 2008). An evaluation of the effects of climate change on three lakes of different morphology and trophic state utilizing DYRESM-CAEDYM models predicted that increased future temperatures will result in increased algal bloom formation and increased presence of cyanobacteria (Trolle et al. 2011).

CE-QUAL-W2

CE-QUAL-W2 is an open source and freeware program supported by US Army Corps of Engineers (USACE) and maintained by the Water Quality Research Group at Portland State University. CE-QUAL-W2 is a water quality and hydrodynamic model in 2-D (longitudinal-vertical) for rivers, estuaries, lakes, reservoirs and river basin systems. The program models basic eutrophication processes such as temperature, nutrient, algae, dissolved oxygen, organic matter and sediment relationships (Cole and Wells 2015). CE-QUAL-W2 has the ability to simulate a user defined number of different phytoplankton groups, zooplankton groups, benthic algae groups, and macrophyte groups. CE-QUAL-W2 does not simulate macroinvertebrate, fish or bird response. CE-QUAL-W2 Version 3.7.2 predicts sediment oxygen demand and nutrient fluxes from the underlying benthos through either zero-order or first-order decay. A fully predictive sediment diagenesis routine is implemented in Beta Version 4.0 of the program.

CE-QUAL-W2 simulates the settling and loss from the system of a user-defined number of sediment size classes. The model does not simulate inorganic sediment accumulation or resuspension; however, a sediment transport module is under development for future versions. In the sediment diagenesis module, organic sediments can be resuspended based on the bottom scour effects of wind action. The adsorption of P to inorganic sediments is simulated based on a partition coefficient, and when settled to the lake bottom is lost from the system. The adsorption and desorption of P onto iron oxyhydroxide in the sediment diagenesis module is dependent on the dissolved oxygen concentration.

CE-QUAL-W2 has been widely applied to lakes and reservoirs in the United States, particularly those managed by the US Army Corps of Engineers (USACE) and US Bureau of Reclamation (USBOR). Several reservoirs in Utah have been modeled using CE-QUAL-W2, including Pineview Reservoir (Tetra Tech 2002), Lake Powell (Williams 2007) East Canyon (JM Water Quality 2008), Deer Creek Reservoir (Obregon 2012) and Rockport Reservoir.

Summary

Table 2 provides a summary of model capabilities as described in the previous sections.

Table 2: Comparison of model capabilities

Model Name	WASP	CAEDYM	PCLAKE	CE-QUAL-W2
Spatial Dimension	1-D	1-D	1-D	2-DV
Stratification	-	-	-	+
Inorganic Sediment Groups	3	6	1	3+
Littoral Zone	-	+	+	-
Phytoplankton Groups	5	7	3	3+
Zooplankton Groups	1	5	1	3+
Benthic Algae Groups	3	4	1	3+
Macrophyte Groups	1	1	1	3+
Macroinvertebrate Groups	0	3	1	0
Fish Groups	0	3	3	0
Bird Groups	0	0	0	0
Hydrodynamics	+	+	±	+
Temperature Dynamics	+	+	±	+
Ice Cover	+	+	-	+
Oxygen Dynamics	+	+	+	+
Inorganic Carbon (CO2/DIC) Dynamics	+	+	-	+
Organic Carbon (DOC/POC) Dynamics	+	+	+	+
Microbial Dynamics	+	+	±	+
Internal Phosphorus Dynamics	+	+	+	+
Phosphorus Adsorption/Desorption	+	+	+	±
Internal Nitrogen Dynamics	+	+	+	+
Internal Silica Dynamics	+	+	±	+
Sedimentation/Resuspension	±	+	+	±
Sediment Diagenesis	+	+	+	+
Clear-Turbid Stable State Transition	±	±	+	±
Fisheries Management	-	±	+	-
Dredging	-	-	+	-
Mowing	-	-	+	-
+ Capable; - Not Capable; ± Partially Capable				

When the models are ranked for each model selection criterion (Table 3), a dichotomy presents itself where the models best suited to the Utah Lake application with regards to complexity and processes simulated (CAEDYM and PCLAKE), are also the least transparent, flexible and compatible due to proprietary licensing (DUFLOW and DYRESM-CAEDYM) and language (PCLAKE). WASP, which is least well-suited in its current form, could most easily be adapted to address the unique characteristics of Utah Lake, as was done for Lake Okeechobee. CE-QUAL-W2 is ranked in the middle for each of the criteria.

Table 3 presents the model ranking for each model selection criterion. EFDC-WASP ranked highest for the appropriate level of complexity to meet the model objectives. Although CAEDYM and PCLAKE simulate ecological response to nutrient levels, calibration would be challenging given the data expected to be available and the added complexity of food web variables would increase model uncertainty. PCLAKE did not meet the minimum requirements for simulating key processes, as it is not capable of simulating pH, which was one of the water quality endpoints included in the model objectives. Although PCLAKE is the only model explicitly developed to predict the clear-turbid stable state transition, the other models were considered to meet this criterion, as the transition can be identified through the predicted biomass of planktonic and benthic algae, and the rooted aquatic vegetation.

As an open source model supported by the EPA, EFDC-WASP also ranked highest for transparency, flexibility and compatibility. ELCOM-CAEDYM and DUFLOW-PCLAKE were considered the least transparent due to proprietary licensing and limited applications and training opportunities in the United States. CE-QUAL-W2 ranked in the middle for each of these criteria.

Table 3: Rank of model for selection criteria

Criteria	DUFLOW-PCLAKE	EFDC-WASP	ELCOM-CAEDYM	CE-QUAL-W2
Complexity (Appropriate Level)	3	1	2	4
Processes (Simulates Key)	D	2	1	3
Data Requirements (Least)	1	3	4	2
Transparency (Most)	3	1	3	2
Flexibility (Most)	4	1	2	3
Compatibility (Most)	4	1	3	2
Ranking scale is from 1 best suited to 4 least suited. D indicates model does not meet minimum requirements of criterion.				

Recommended Model

The EFDC-WASP model is recommended for selection since it has the most appropriate level of complexity to address the modeling objectives, and is also considered the most transparent, flexible, and compatible. Although WASP ranked below CAEDYM in ability to simulate key processes, this could be addressed through modifications to the source code to improve phosphorus sorption dynamics and coupled with a food web model to capture ecological response.

ELCOM-CAEDYM is also considered to have strong capabilities to address the modeling objectives; however, there are concerns about model calibration and uncertainty due to the increased complexity associated with simulating response of ecological variables. The model also ranked lower for its transparency, flexibility and compatibility than EFDC-WASP.

PCLAKE does not simulate pH, which was one of the key response parameters to eutrophication and critical to phosphorus sorption dynamics. CE-QUAL-W2 ranked in the middle for most of the selection criteria and its ability to simulate vertical stratification was not considered critical to shallow lakes.

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