Utah Lake Water Quality Study—Conceptual Models

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PRESENTED TO

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Cover image: Image of Utah Lake. Source file available at https://deq.utah.gov/communication/state-of-the-environment-report/utah-lake-study-2018-state-of-the-environment-report-wq

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ABBREVIATIONS

Abbreviation	Definition
Al	Aluminum
Ca	Calcium
EFDC	Environmental Fluid Dynamics Code
Fe	Iron
N	Nitrogen
NH4	Ammonium
NO3	Nitrate
NO2	Nitrite
P	Phosphorus
PO4	Phosphate
PON	Particulate Organic Nitrogen
POP	Particulate Organic Phosphorus
SP	Science Panel
UDWQ	Utah Department of Water Quality
ULWQS	Utah Lake Water Quality Study
WASP	Water Quality Analysis Simulation Program

1.0 BACKGROUND

The goal of the Utah Lake Water Quality Study (ULWQS) is to evaluate the effect of nutrients on the support of designated uses in Utah Lake, with a focus on development of in-lake water quality criteria that are protective of the lake's designated uses. The ULWQS Science Panel (SP) is tasked with guiding water quality criteria development on Utah Lake by overseeing targeted scientific studies. The panel is working under a charter, a set of operating principles including six significant tasks, and a set of high-level specific initial charge questions which are, at a distilled level: 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?; and 3) What additional information is needed?

Answering these questions will require research to evaluate and communicate the important pathways through which nutrients influence assessment endpoints and management goals for the lake and the factors that modify those pathways. Conceptual models are an important component of this effort. They help synthesize existing knowledge, identify knowledge gaps, and highlight important relationships to model and understand. Conceptual models can be targeted at a variety of audiences.

This memo presents several conceptual models of nutrient effects in Utah Lake. Each model is accompanied by a brief narrative. It ends with a brief discussion of the relative extent to which the mechanistic models using EFDC and WASP being developed by University of Utah engineers and scientists to simulate water quality in Utah Lake capture the pathways described in the model narratives.

2.0 SIMPLIFIED NUTRIENT MODEL

The simplified nutrient model (Figure 1) is the first model described.

2.1 NARRATIVE

The principal nutrients that influence management goals and considered in this model for Utah Lake include nitrogen and phosphorus. These nutrients in Utah Lake are derived from three main sources: the watershed, the atmosphere, and from internal cycling (recycling from the sediments). The atmospheric and watershed sources are considered “new” inputs of nutrients, whereas previously delivered watershed loads are recycled as internal sources. Atmospheric sources of phosphorus and nitrogen include dry and wet deposition, as well as gaseous sources for nitrogen.

These nutrients recycle within the dissolved nutrient pool via microbial uptake and transformations of nitrogen. Some of the dissolved nutrients adsorb onto or form complexes with inorganic particles and solutes dissolved in the water column (e.g., calcite scavenging of phosphorus). These particles can settle out into the sediment or the nutrients may desorb back into the water column dissolved nutrient pool.

Dissolved nutrients are taken up by algae in the water column and algae and plants growing on and in the sediment. Benthic plants also take up nutrients from the sediment themselves. The algae in the water column enter the food web through consumption by zooplankton which are, in turn, consumed by fish. Benthic plants and algae are grazed by benthic invertebrates and some fish species. All these animals excrete nutrients, which are recycled back into dissolved nutrient pools in the lake. When the organisms defecate or die, nitrogen and phosphorus associated with their feces and bodies enter detrital pools, which are decomposed by microbes and consumed by detritivores. This results in the release of dissolved nutrients into sediments or back into the water column nutrient pool. Ultimately, a portion of the nutrients entering the lake are recycled through the food web and between water column and sediment pools. Some portion of the dissolved or particulate nutrients are exported downstream via the Jordan River, some enter permanent sedimentary pools via burial, and some nitrogen is released back to the atmosphere in gaseous form.

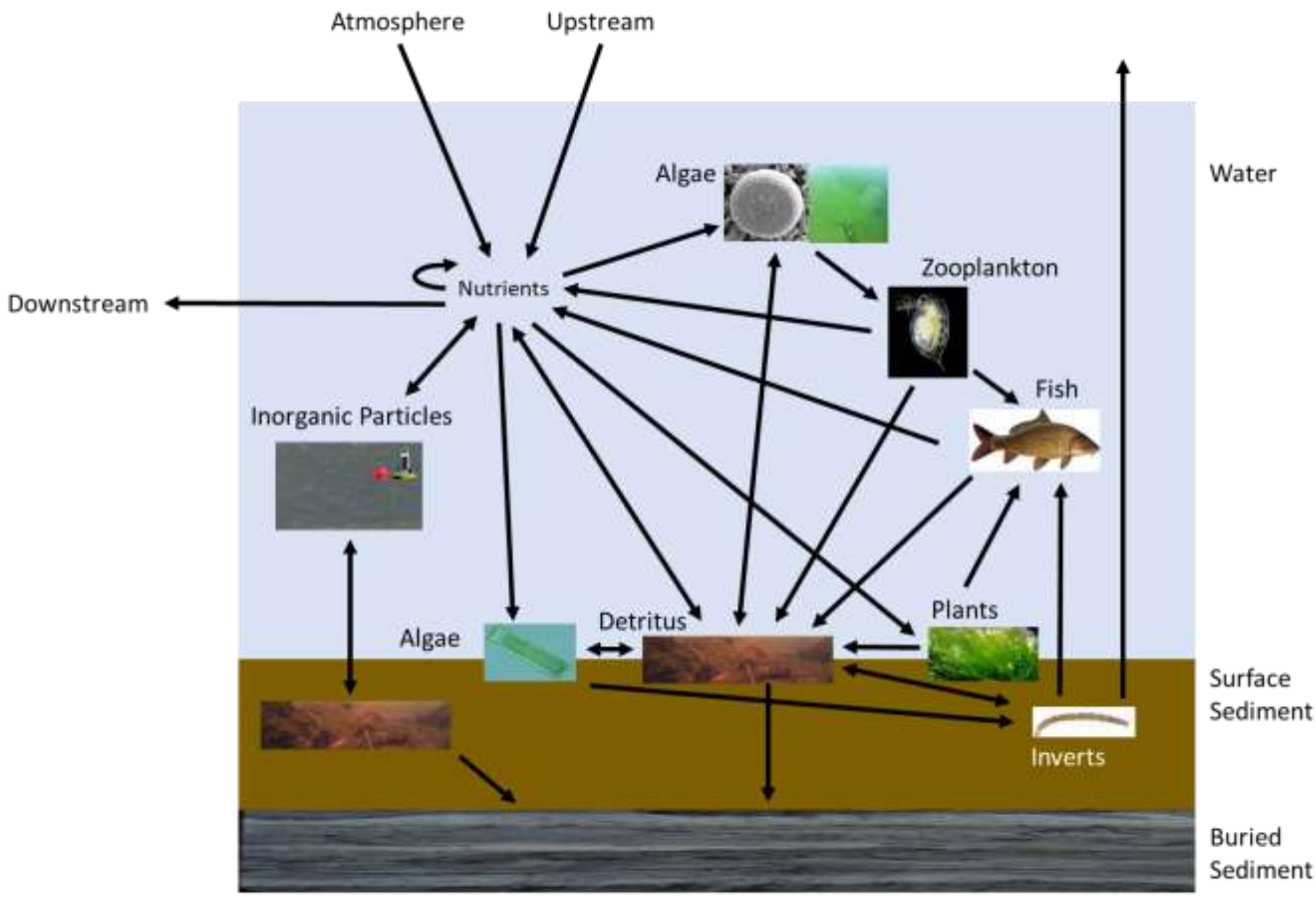

Figure 1. Simplified nutrient model

3.0 CAUSAL MODEL

The causal model (Figure 2) is derived from the ecological risk assessment approach. This formulation is derived from the USEPA Causal Analysis/Diagnosis Decision Information System (CADDIS) approach (https://www.epa.gov/caddis). This modeling approach focuses on the pathways through which a stressor (nutrient pollution) is generated from sources and ultimately affects management goals. It attempts to capture important modifying factors as well.

3.1 NARRATIVE

The causal model traces sources of nutrients from anthropogenic and natural stocks to impacts on assessment endpoints and management goals through flow pathways that describe how the nutrients are cycled and modified by external drivers.

The model depicts nutrients being generated from several watershed sources: natural land sources (geology, soils, etc.), and from human landscape sources including agriculture, silviculture (forestry), urbanization and industrial sources. These sources generate nitrogen (N) or phosphorus (P) that increase in soils, in wet or dry deposition, and in discharges to surface waters. These result in increased nutrients in subsurface groundwater and surface runoff.

This enriched water then enters the water column of the lake via groundwater or tributaries. Some of these inputs enter lake sediment pools, increasing N and P there. Dissolved inputs enter the water column dissolved N and P pools, whereas particulate inorganic and organic N and P from runoff enter their respective pools in the water column or sediments.

The dissolved and particulate N and P can then cycle through the food web, from which dissolved and particulate N and P may return to the water column of be exported to the sediment. Dissolved P in the water column or sediments interact with solutes (e.g., Ca, Fe, Al) to regulate the movement (e.g., via adsorption/desorption, solution/dissolution) of P between dissolved and inorganic particulate pools. This regulation is influenced by pH and reduction-oxidation potential. Nutrients then have two main pathways by which they can influence responses: through their effects on primary production leading to greater organic matter loading and oxygen demand and by their influence on competition and a change in assemblage structure that can favor nuisance taxa. Along the first path, dissolved N and P is taken up by phototrophs to enhance primary productivity. This response is regulated by a variety of factors including temperature, which itself is influenced by depth, and light. Light is, in turn, influenced by turbidity caused by suspended sediments from runoff, wind and bioturbation.

Increased primary productivity leads to increased organic matter. The enhanced organic matter then fuels increased microbial productivity associated with decomposition which drives increased respiration. The same microbes are also, themselves, directly enriched by dissolved N and P. The increased respiration alters dissolved oxygen concentrations and pH, both of which affect aquatic life. Increased organic matter can also alter habitat structure (via effects on clarity or benthic habitat) for aquatic life.

Simultaneously, increased N and P also alter competition among phototrophs, with enrichment tending to favor common nuisance taxa (e.g., *Microcystis*), many of which have higher half saturation constants for P and N. A change in assemblage structure can alter food resources (e.g., leading to less palatable species for zooplankton) and to the proliferation of nuisance taxa that produce harmful algal toxins. There are factors (e.g., temperature) that affect toxin production, the science for which is still unsettled, thus, the question mark. These toxins can impact agricultural and recreational uses. An increase in nuisance taxa biomass can also lead to reduced clarity and surface scums which may also reduce recreational uses and to a proliferation of taste and odor compounds (e.g., 2-methylisoborneol) that can influence agricultural and recreational uses.

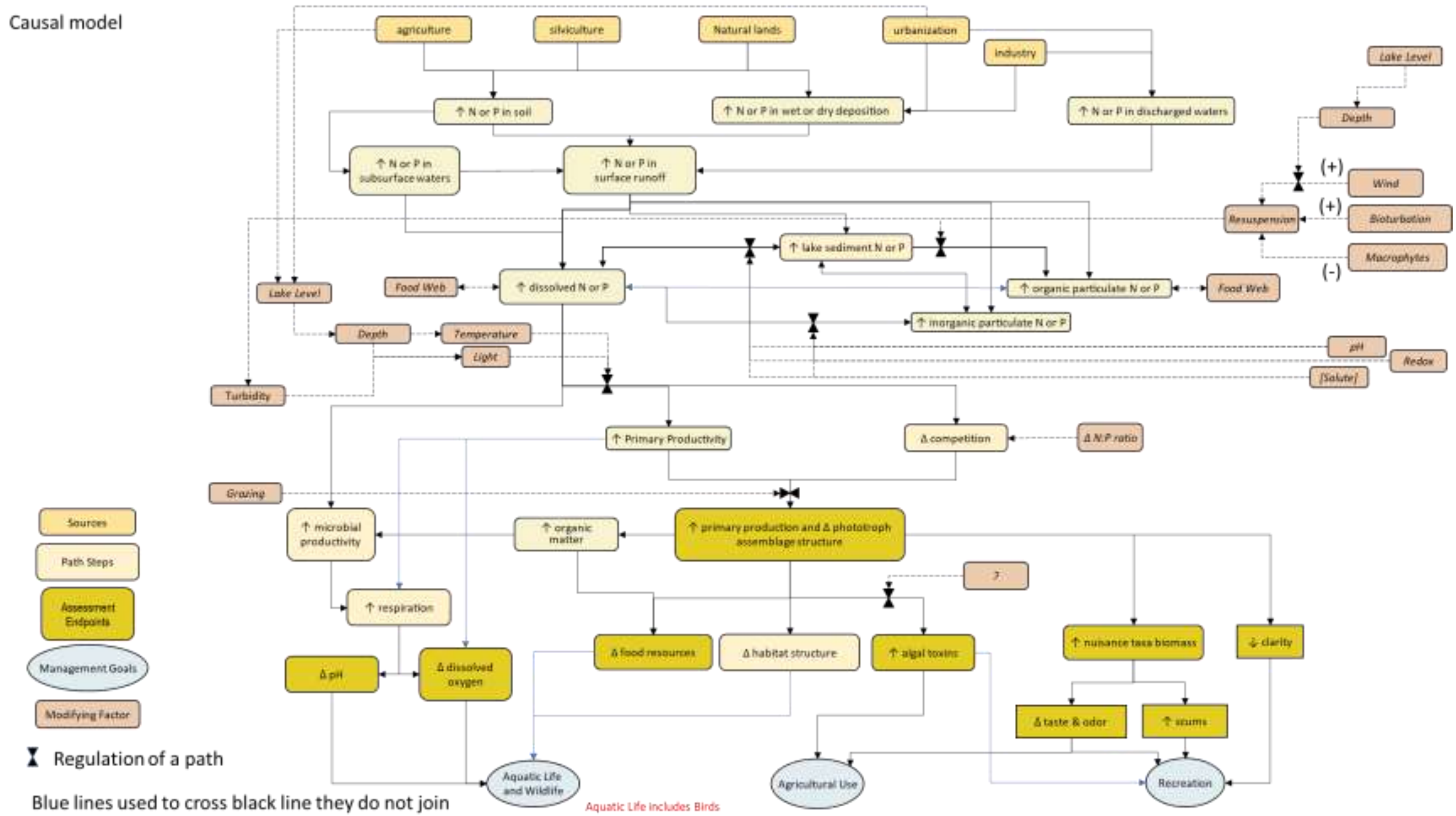

Figure 2. Causal Model

4.0 NUTRIENT CYCLING MODELS

The nutrient cycling models provide greater detail on specific nutrient transformations and movements within Utah Lake. They are split into phosphorus and nitrogen models. Each has call out boxes that further explain some of the details.

4.1 PHOSPHORUS MODEL NARRATIVE

Phosphorus is imported to- and exported from Utah Lake in three main forms: particulate, colloidal, and dissolved fractions, entering via tributary runoff, groundwater inputs, and atmospheric deposition and leaving primarily via downstream transport (Figure 3). Dissolved P in the water column or sediments interacts with solutes (e.g., Ca, Fe, Al) to regulate the movement (e.g., via adsorption/desorption, solution/dissolution) of P between dissolved and particulate pools. This regulation is influenced by pH and reduction-oxidation potential.

Dissolved P is also taken up by primary producers (which are also regulated by light and temperature, among other factors) and microbes which are, in turn consumed by primary consumers, and those by secondary consumers. A portion of the consumer P may leave the lake via emergence, harvest, or downstream transport. P is returned to the dissolved pool by excretion from organisms and, when organisms die, P enters the detrital pool which microbes consume, cycling P back into the food web.

A certain portion of particulate and colloidal P enters the sediments via settling and is returned to the water column via resuspension, controlled by wind and bioturbation. Similarly, dissolved P can move from the water column to the sediments and vice-versa through diffusive exchange. Within or on sediments, similar movement of P takes place within the dissolved P, food web, and detrital P pools as described for the water column. A portion of particulate P enters permanent sediment storage pools via burial.

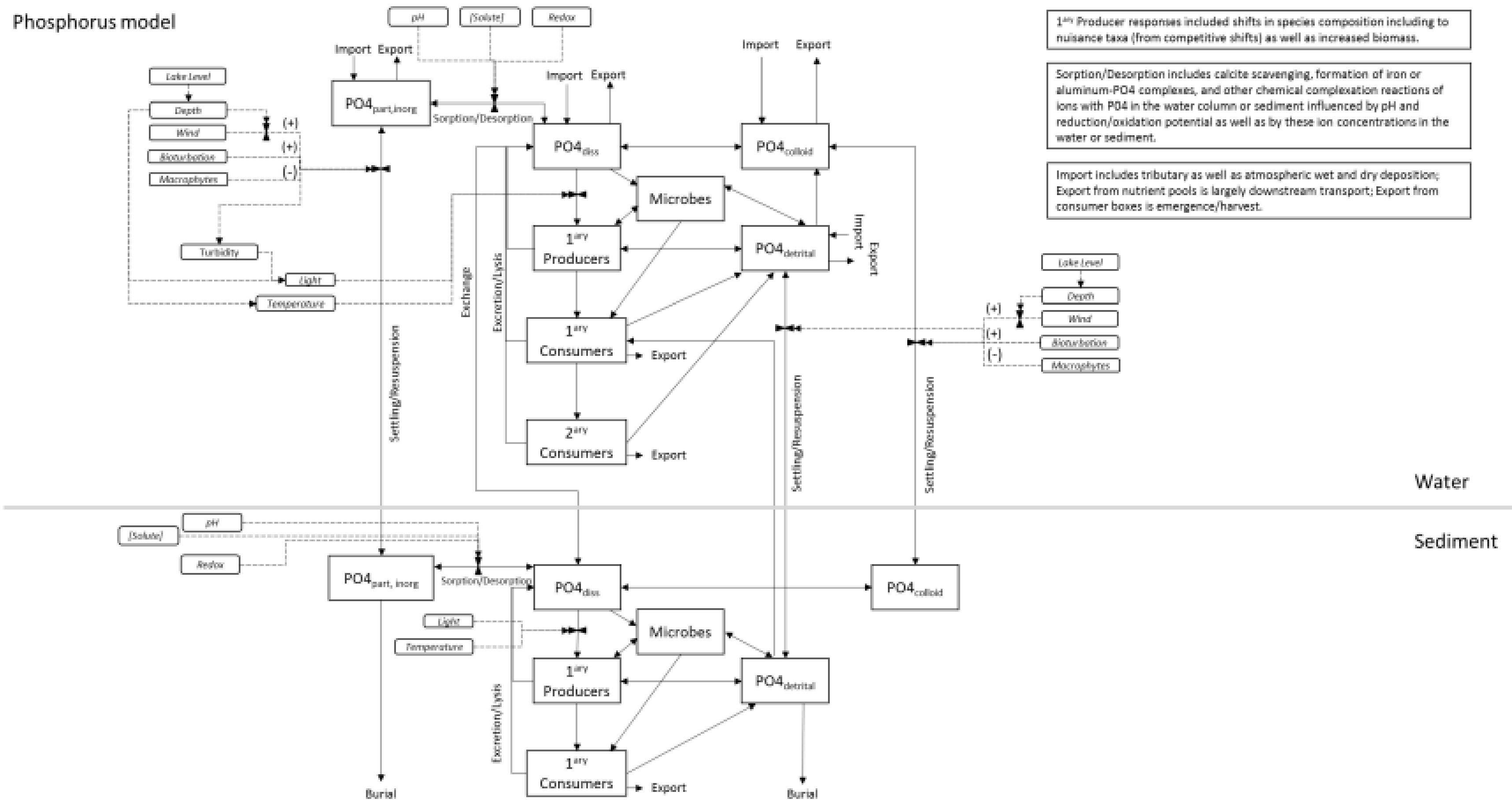

Figure 3. Phosphorus nutrient model

4.2 NITROGEN MODEL NARRATIVE

Nitrogen cycling is more complex in lakes due to the variety of forms N can take (including gaseous forms) and the greater variety of microbial transformations controlling N cycling (Figure 4). N is imported into dissolved N pools in the water column via tributary runoff, groundwater inputs, direct atmospheric deposition, and via nitrogen fixation. Dissolved N is exported from the lake via downstream transport and denitrification and anaerobic ammonium oxidation.

Within the dissolved N pool, there are a variety of microbially mediated reactions that drive exchanges between ammonium, nitrite and nitrate. Ammonium and nitrate are taken up by primary producers, regulated by light and temperature, and by microbes. From these pools, nitrogen can move to primary consumers and secondary consumers through the food web. A portion of the consumer N may leave the lake via emergence, harvest, or downstream transport. Through excretion and lysis, N is returned to the dissolved pool and through death and excretion, N enters the detrital pool which microbes consume, cycling N back into the food web.

A certain portion of particulate N enters the sediments via settling and is returned to the water column via resuspension, controlled by wind and bioturbation. Similarly, dissolved N can move from the water column to the sediments and vice-versa through diffusive exchange. Within or on sediments, similar movement of N takes place within the dissolved, food web, and detrital N pools as described for the water column. A portion of particulate N enters permanent sediment storage pools via burial.

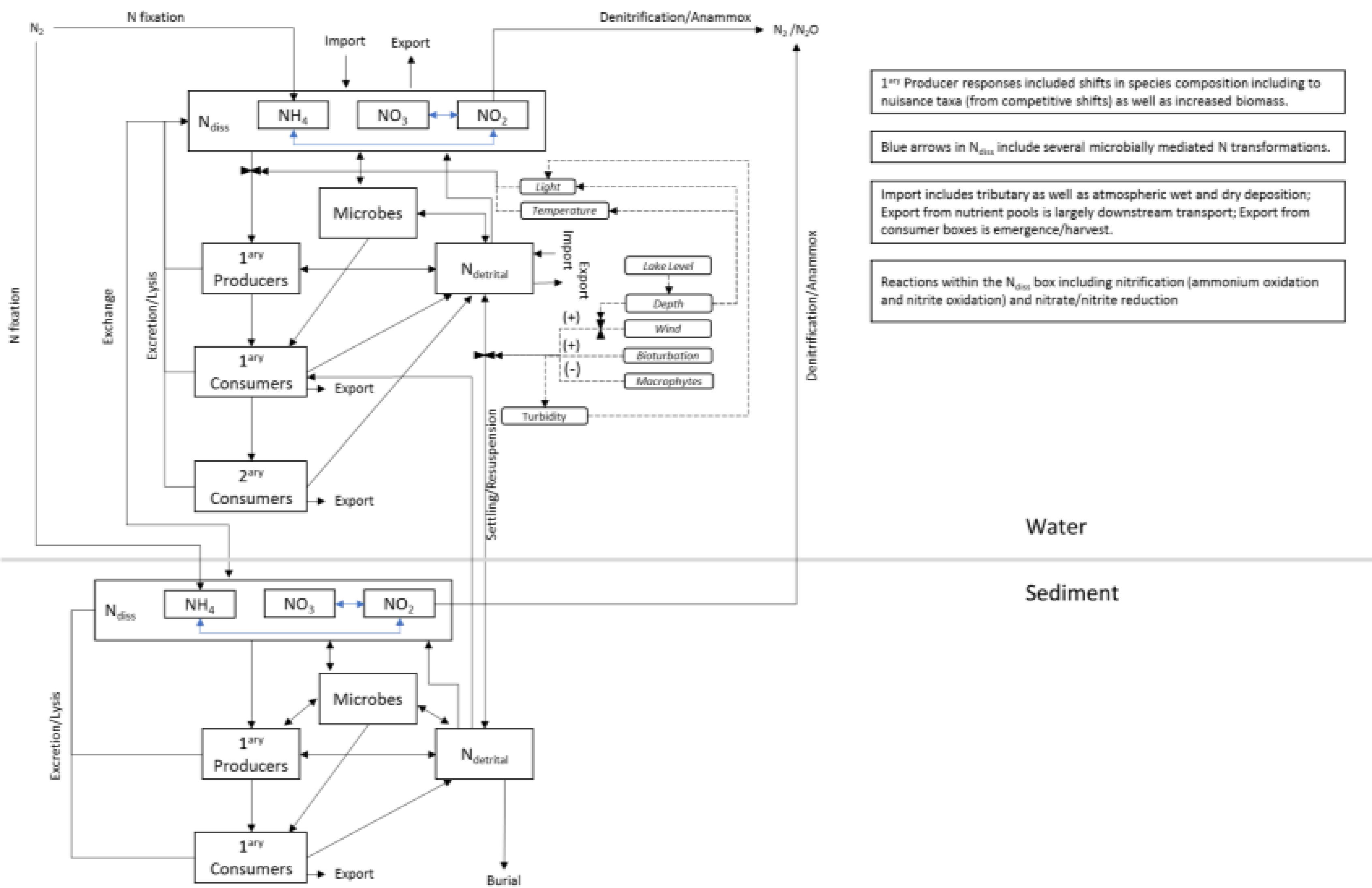

Figure 4. Nitrogen nutrient model

5.0 ECOSYSTEM MODEL

The ecosystem model (Figure 5) is somewhat of a compromise between the causal and nutrient models. It focuses on the major pools of nutrients in the system and flows among them.

5.1 NARRATIVE

N and P enter dissolved and particulate pools from the watershed and atmosphere via groundwater, tributary runoff, wet and dry deposition and, in the case of N via N fixation. Chemical reactions with solutes (e.g., Ca, Fe, and Al), dependent on pH and reduction-oxidation state, govern movements (e.g., sorption/desorption) between the dissolved and inorganic particulate phases. A portion of dissolved N may be returned to the atmosphere via denitrification and anaerobic ammonium oxidation and some dissolved and particulate N and P is lost via downstream transport.

Dissolved N and P are taken up from the water column and sediments by algae and microbes, which can also access particulate bound nutrients via enzymatic reactions, and macrophytes. This primary producer pool is consumed in turn by zooplankton and benthic invertebrate herbivores, which themselves are consumed by invertebrate and vertebrate secondary consumers. Through excretion, lysis, and death, nutrients move back to the dissolved pool or the detrital pool. The latter is either consumed by microbes, cycling nutrients back into the food web via the microbial loop, or lost via downstream transport.

A portion of inorganic and organic particulate nutrient pools exchange with the sediments via settling and resuspension, controlled by wind and bioturbation. In addition, there is movement between water column and sediment dissolved nutrient pools via diffusive exchange. In the sediments, nutrients can move similarly between dissolved, and particulate forms via the food web. A portion of sedimentary nutrient pool may be permanently removed via burial.

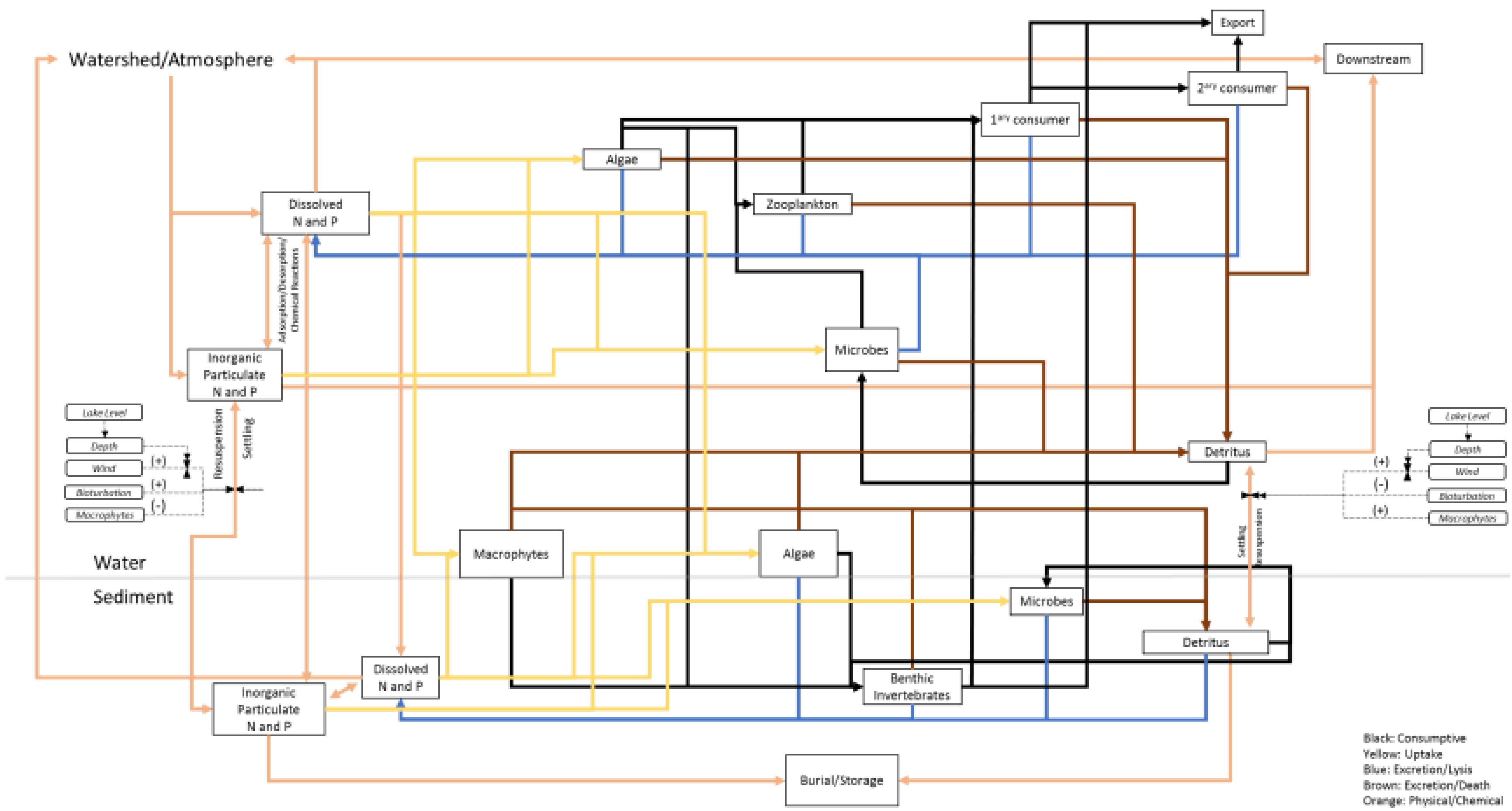

Figure 5. Ecosystem model

6.0 MECHANISTIC MODELING COMPARISON

Model engineers and scientists working at the University of Utah (Juhn-Yuan Su) and UDWQ (Nick Von Stackelberg) were asked to review the models above for those components that are simulated or not simulated by the mechanistic models. This section briefly highlights the feedback from those technical experts.

6.1 CAUSAL MODEL

The following elements of the causal model are not simulated in WASP or EFDC

Modifying Factors

- Turbidity: This parameter is currently not incorporated in this version as a state variable and hence is not modeled in WASP. Since WASP does not simulate turbidity, WASP will not simulate the effects of phytoplankton upon water clarity. However, EFDC does simulate classes of inorganic suspended sediment which can be used to simulate turbidity.
- Food Web: WASP is not implemented as a food web model and hence does not incorporate any food web processes nor any aquatic life or wildlife response explicitly.

Path Steps/Assessment Endpoints

- Inorganic Particulate N and P: WASP simulates the dissolved inorganic species (N and P). Inorganic Particulate N and P is incorporated in WASP through the simulation of benthic N and P rates under the sediment diagenesis routine. WASP does NOT simulate particulate inorganic N and P as separate state variables.
- Other Parameters: WASP does not simulate changes in food resources and habitat structure nor any changes in competition outside of nutrient uptake kinetics. Similarly, taste and odor or scums are not simulated directly.

Meanwhile, the following components can be represented in WASP but may exhibit significant limitations.

Modifying Factors

- Grazing: WASP incorporates grazing characteristics through the palatability of each phytoplankton group. WASP does not incorporate other grazing processes.

Path Steps/Assessment Endpoints

- Change in N and P in subsurface waters: WASP can incorporate groundwater inflow quantity and quality into the Utah Lake model, which currently includes 4 groundwater sources (Northern Valley, Southern Valley, Provo Bay, Goshen Bay). On the other hand, such groundwater inflows serve as inputs into WASP and are not simulated separately as no groundwater models have been applied.
- Algal Toxins: WASP only simulates the concentrations of phytoplankton and algae and does not simulate toxins.

6.2 NUTRIENT CYCLING MODELS

The following elements of the nutrient cycling models are not simulated in WASP or EFDC

- Primary and Secondary Consumers: Since WASP is not a food web model, the export of phosphorus/nitrogen from primary and secondary consumers are not incorporated into the model. For WASP, the user can only implement zooplankton population (per model segment/node) and edibility or palatability fractions (per phytoplankton group) to simulate food web processes, but the significance of these parameters upon the model performance (e.g., phytoplankton chlorophyll-a concentrations, nutrient concentrations, etc.) is being investigated.
- Adsorption/Sorption/Desorption of Phosphorus: WASP allows the user to simulate up to 10 solids groups for the purposes of applying solids transport. Meanwhile, the user can define adsorption coefficients for phosphorus into each solids group. On the other hand, apart from the input parameters for solids transport and for adsorption coefficients for N and P into each solids group, WASP appears to treat all solids group uniformly.
- Colloidal Phosphate: WASP does allow the user to specify coefficients for adsorption of phosphate to water column solids, with separate adsorption coefficient per solids group (e.g., one per clay, one per sand, etc.). On the other hand, WASP does not simulate inorganic particulate N and P as separate state variables from the dissolved inorganic N and P species. Hence, the representation of colloidal P seems to be rather limited in WASP.
- Microbes on Particulate Organic Decomposition: WASP simulates the concentration of detrital phosphate/particulate organic phosphate) through the sediment diagenesis routines but does not simulate the decomposition of particulate organic phosphorus (POP) by microbes. WASP appears to not simulate the decomposition of detrital nitrogen/particulate organic nitrogen (PON, only simulating the concentrations of particulate organic nitrogen (PON) rather than the decomposition of PON.
- Nitrate and Nitrite Nitrogen: WASP simulates nitrate and nitrite as a combined state variable (e.g., nitrate-nitrite nitrogen rather than nitrate from nitrite).
- Turbidity: WASP does not simulate turbidity as a state variable but the EFDC model can simulate this as described for the causal model.

6.3 ECOSYSTEM MODEL

- Primary and Secondary Consumers for Nitrogen: Similar to the comments for the nutrient cycling model, WASP does not simulate the export of nutrient species from primary and secondary consumers.
- Microbes: WASP simulates the concentration of detrital phosphate/particulate organic phosphate) through the sediment diagenesis routines but does not simulate the decomposition of POP by microbes. WASP appears to not simulate the decomposition of detrital nitrogen/PON (only simulating the concentrations of PON rather than the decomposition of PON).
- Nitrate and Nitrite Nitrogen: As stated for the nutrient cycling model, WASP simulates nitrate and nitrite as a combined state variable (e.g., nitrate-nitrite nitrogen rather than nitrate from nitrite).
- Turbidity: As discussed in previous comment for nutrient cycling, WASP does not simulate turbidity as a state variable but the EFDC model can simulate this as described for the causal model.