Lake Erie Millennium Network

Visualizing an Updated Understanding of Lake Erie Eutrophication – a Fuzzy Cognitive Mapping Workshop

Report

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Meeting Purpose and Goals

The overarching workshop purpose was to bring together experts with various perspectives to visualize a broad, general view of the problem of Lake Erie eutrophication using the process of creating fuzzy cognitive maps (FCMs). As well as addressing the goals outlined below, the workshop was designed to promote focused discussion and networking among experts across disciplines, cultivating future collaborations. This was the latest in a series of workshops and synthesis exercises convened by the Lake Erie Millennium Network to understand changes and processes in the Lake Erie ecosystem.

This project builds on past efforts (detailed below) and is led by Rebecca Rooney (University of Waterloo) and Jan Ciborowski (University of Windsor). It is funded through the Lake Futures component of the Global Water Futures project, led by the University of Saskatchewan. Our hope is to complement this workshop with another that brings in stakeholders and the public to conduct a similar exercise so we can compare perspectives from both groups.

Goals

1) Develop a broad visualization of causes and manifestations of eutrophication in Lake Erie as understood by experts;
2) Compare the resultant visualization with findings of previous FCM exercises done in 2009-2014 to elucidate evolution in understanding;
3) Identify areas of disparity in the understanding of drivers and outcomes of eutrophication, indicating potential knowledge gaps and areas for future research; and
4) Serve as a first step in comparing the perspectives of invested audiences, with this workshop documenting the perspectives of researchers and managers, and future efforts focusing on stakeholders and the public

Background

Eutrophication is one of the issues that the International Joint Commission addressed during its 2007-2009 priorities cycle, with special focus on the causes of eutrophication within the Lake Erie basin (Dundas and Gannon 2009). This investigation included several workshops (2009-2014) convened to identify and visualize the relationships among factors involved in eutrophication at various levels of focus. Early work on the topic had focused on the effectiveness of municipal, point source effluents as Canada and the U.S. brought nutrient loadings under control following implementation of the Great Lake Water Quality Agreement. However, the reappearance of episodic algal blooms in the mid 2000s led to a search for other causes or explanations, including more focus on the influence of agriculture.

A notable challenge in addressing eutrophication is the fact that it is difficult to define. We can identify manifestations of eutrophication, but the concept of eutrophication itself is ill-defined. However, one could argue that if the undesirable indicators of eutrophication are brought under control, then the eutrophication problem would be resolved. The 2012 renewal of the Great Lakes Water Quality Agreement (GLWQA) would consider the extent of hypoxic zones, algal species consistent with nearshore aquatic health, the impact of toxin concentrations from cyanobacteria biomass on human and ecological health, and the ecological state of Lake Erie as important indicators that should be controlled to reduce eutrophication.

Methods

Participants: Seventeen participants (Appendix 1) with expertise in various areas related to water quality and ecosystem health in Lake Erie convened on March 12-13, 2019, at the University of Windsor, to create fuzzy cognitive maps (FCMs) representing their understanding of eutrophication in Lake Erie. Fuzzy cognitive mapping allows experts to graphically arrange key variables (concepts) and their interrelationships, organizing their understanding of the components of the issue into a cognitive map of the process of eutrophication. The combination of the separate maps into one map produces the consensual FCM.

Preparation: Before the workshop, participants were asked to review two iterations of a list of concepts for use during the workshop. The original list of concepts was generated from concepts identified at three previous workshops. The inaugural workshop (Dundas and Gannon 2009) produced a useful summary of concepts understood at the time. It also revealed the complexity of the phenomenon and the ambiguity of some of the key variables identified by the participants. As a result, follow-up workshops were convened in 2010, 2013 and 2014, which focused on the effects of agricultural (Martin et al. 2010) and urban influences (ref 2014), respectively. The preliminary list of variables offered to participants of the current workshop included concepts used in maps created at those previous workshops.

Participants were asked to rate the importance of each concept and identify where concepts were redundant or missing. The final concept list was printed on stickers and distributed to each team at the workshop. All concepts that were made available for use at the workshop are given in Appendix 2.

Workshop Activities: At the workshop, participants were assigned to 4- or 5-person breakout teams each of which had a broad spectrum of expertise and perspectives. Each team worked independently to create an FCM using the concept stickers provided and large pads of paper. Periodically, the entire group would reconvene to discuss any issues that had arisen or vet any new concepts proposed by a breakout group.

After placing stickers on the paper, teams drew arrows to connect related concepts, indicating instances where one concept (a 'transmitter') is expected to influence another (a 'receiver') (Özesmi and Özesmi 2004). Strengths (1-5) and signs (+/-) were assigned to each arrow, with 5 indicating a very strong relationship, and 1 indicating a weak one. A positive relationship (+) indicates that an increase in the transmitter would result in an increase in the receiver, and a negative relationship (-) indicates an inverse relationship (i.e. an increase in the transmitter would be associated with a decrease in the receiver).

At the end of the workshop, the entire group reviewed each team's map, and each breakout group explained the details of their map to the rest of the participants. These group-specific discussions are summarized below. A whole-group discussion followed and focused on how best to integrate and build on outcomes of the workshop.

Compilation and Data Analysis: Following the workshop, each team's map was digitized and converted into an adjacency matrix, where each row and column represents a concept, and the cell values represent the strength of the relationship between the row (transmitter) and column (receiver) (Özesmi and Özesmi 2004). The individual matrices were then consolidated into a single consensual FCM using a modified version of the FCMapper package (Turney and Bachhofer, 2016) in R version 3.4.3 (R Core Team, 2017). We modified the FCMapper code by including a weighting factor, which represented the proportion of individual maps on which a relationship was included (i.e., the final relationship importance was the average non-zero assigned strength on individual FCMs multiplied by the proportion of individual maps on which it appeared). Concept indices (indegree, outdegree, centrality, and ubiquity) were determined for concepts in the consensual FCM. Indegree is the absolute sum of all relationships influencing a concept. Outdegree is the absolute sum of all relationships that a concept influences. Centrality is the sum of indegree and outdegree. Ubiquity is the proportion of team maps that included the concept. Matrix indices (number of relationships [=connections], connection density, number of concepts, number of transmitters [variables whose indegree = 0], number of receivers [variables whose outdegree = 0], average number of connections for each concept, and complexity [receivers/transmitters]) were compared among the four team FCMs and the final consensual FCM.

RESULTS

Maps

Photos of each team's hand-drawn map are shown in Appendix 3. Metrics of the four group FCMs, as well as the consensual FCM, are given in Table 1. Each team's digitized map is illustrated in Figures 1 through 4. The overall consensual map is given in Figure 5.

Table 1: fuzzy cognitive map metrics for individual team maps and the consensual FCM. Definitions or formulae as described in Methods

Metric	Team 1	Team 2	Team 3	Team 4	Consensual FCM
# Connections	112	97	80	143	382
Connection density	0.0291	0.0288	0.0433	0.0254	0.0283
# Concepts	62	58	43	75	116
# Transmitters (T)	15	7	8	13	14
# Receivers (R)	3	6	7	13	10
Avg # connections/ variable	1.81	1.67	1.86	1.91	3.29
Complexity (R/T)	0.200	0.857	0.875	1.00	0.714

Team 1

Team 1 created a modular map containing three distinct sections corresponding to parts of the lake: watershed, nearshore, and offshore. As there was no general air temperature concept, they interpreted the average winter temperature as overall temperature – but there are nuances, especially with stratification and hypoxia, that are lost by not splitting out summer temperature as a distinct concept. Team 1's map formed an hourglass shape, with all the effects of all transmitters influencing the tributary concepts before being expressed in the lake. They noted that there was a lot of complexity in the watershed and the lake sections, but that few relationships connected the two. The team noted that few concepts dealt with the movement of materials from land surfaces to tributaries or the lake, or with instream processing and water storage.

The team noted that concepts generally referred to nutrient concentrations, when they felt that nutrient loading was more important. As they built the map, they interpreted the concentration concepts as loadings instead (e.g., SRP concentration to phytoplankton biomass was interpreted as SRP loading to phytoplankton biomass).

When asked what concepts defined eutrophication in their map the group identified phytoplankton biomass, HABs, cyanobacterial biomass, and benthic nuisance algal biomass. They did not include beach closures as a concept in their map, but this could also be included in the list of eutrophication indicators.

The ultimate drivers of eutrophication in Team 1's map were focused around phosphorus, which was critical, as well as increased rainfall driving increased loading. There was uncertainty around the duration of stratification and water temperatures driving hypoxia.

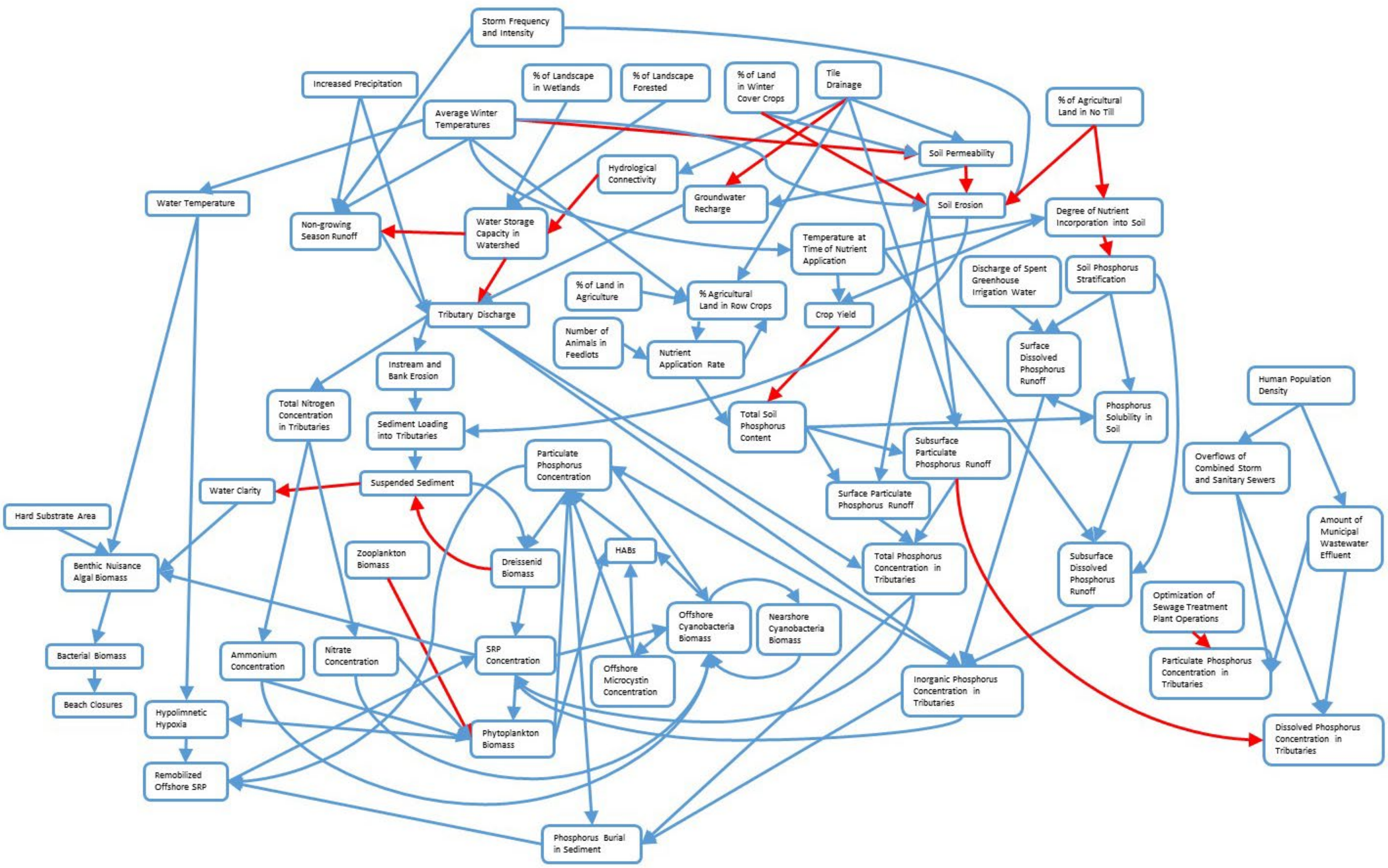

Figure 1: Fuzzy cognitive map created by Team 1. Positive relationships are denoted by blue arrows. Negative relationships are denoted by red arrows.

Team 2 (The Klingon High Council)

Team 2 created a modular FCM divided among three sheets of paper (nearshore, agriculture, and greenhouses and in-lake processes; Appendix 3), though connections existed between sheets of paper.

In general, the group tended toward simplification – with some concepts acting as proxies for other concepts that were not included, even whole processes. The team marked concepts they had identified as drivers in blue and defining aspects of eutrophication in pink. They noted that many of the identified drivers are not conducive to management, and other factors are not well-understood, particularly the social factors affecting concepts on the land. The team noted that the FCM does not have a spatial dimension, so some spatial variability in the existence or strength of relationships (e.g., among basins) is not captured.

The agriculture component of the FCM focused on soil processes, but also included social factors in the agricultural sector. Greenhouses are a growing sector, not included in previous FCM efforts. In the greenhouses and in-lake module of the map, the processes driving greenhouse growth and outputs were included in the point source concepts. They could have also been included in the non-point concepts, and the map would function the same way. The team noted that some greenhouses are connected directly to the municipal wastewater treatment plants. Many greenhouses recycle their water several times, and the effluents have very high concentrations of nutrients.

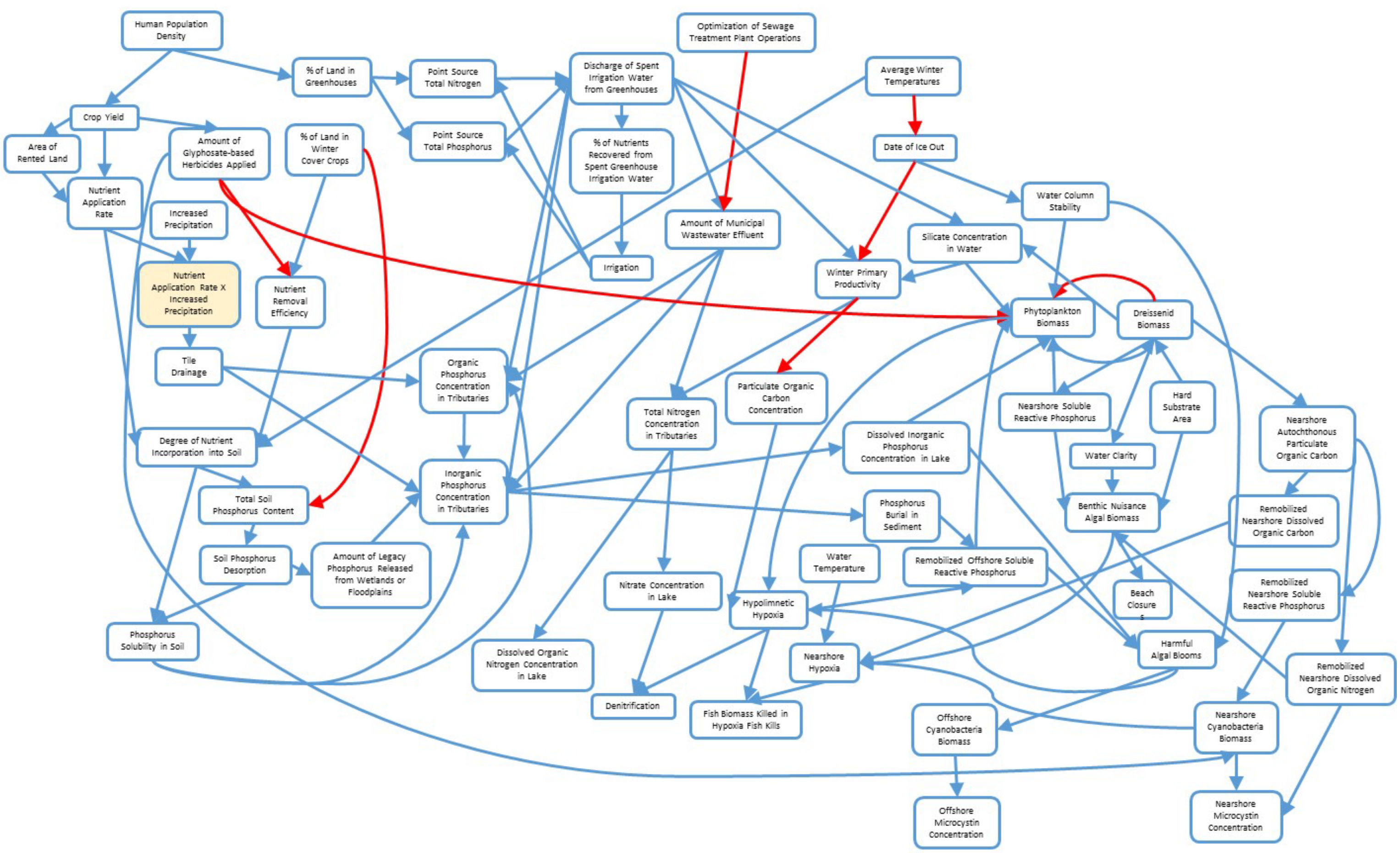

Figure 2: Fuzzy cognitive map created by Team 2. Positive relationships are denoted by blue arrows. Negative relationships are denoted by red arrows. The shaded yellow concept was an interaction concept that was developed by Team 2 and was not available to other teams.

Team 3 (Keep It Simple)

Team 3 tried to keep their map very simple and structured it as a continuous flow modular model. They defined eutrophication through the amount of particulate organic carbon, which is driven by nutrient loads. Upstream processes flow to runoff, which flows into the lake, is subjected to in-lake processes, and then influences eutrophication. They organized on-land processes into urban and agricultural components. Throughout the flows, they tried to keep nitrogen and phosphorus variables separate. The team noted that we need to keep in mind that the concentrations of nutrients that we measure in the water are not driving biology but are the residuals of biological activity. Phosphorus may constrain biomass to a greater degree than nitrogen, but nitrogen may define the type or species that constitute the algal biomass.

The group made two major assumptions: that bacteria are ubiquitous throughout the map; and that storm frequency and intensity will increase through time. They noted that some relationships were nonlinear and so could be either positive or negative depending on conditions. However, because of the limitations of the FCM methodology, they had to choose one sign for each relationship based on what they felt dominated the relationship under expected conditions. The team noted that this choice overly simplified some relationships in the map.

The team interpreted tile drainage as a pathway for nutrients into the lake, so both feedlots and nutrient application rate led into tile drainage with the understanding that increasing nutrient application rates and nutrient runoff from feedlots would increase the magnitude of the nutrients entering the lake through the tile drainage pathway.

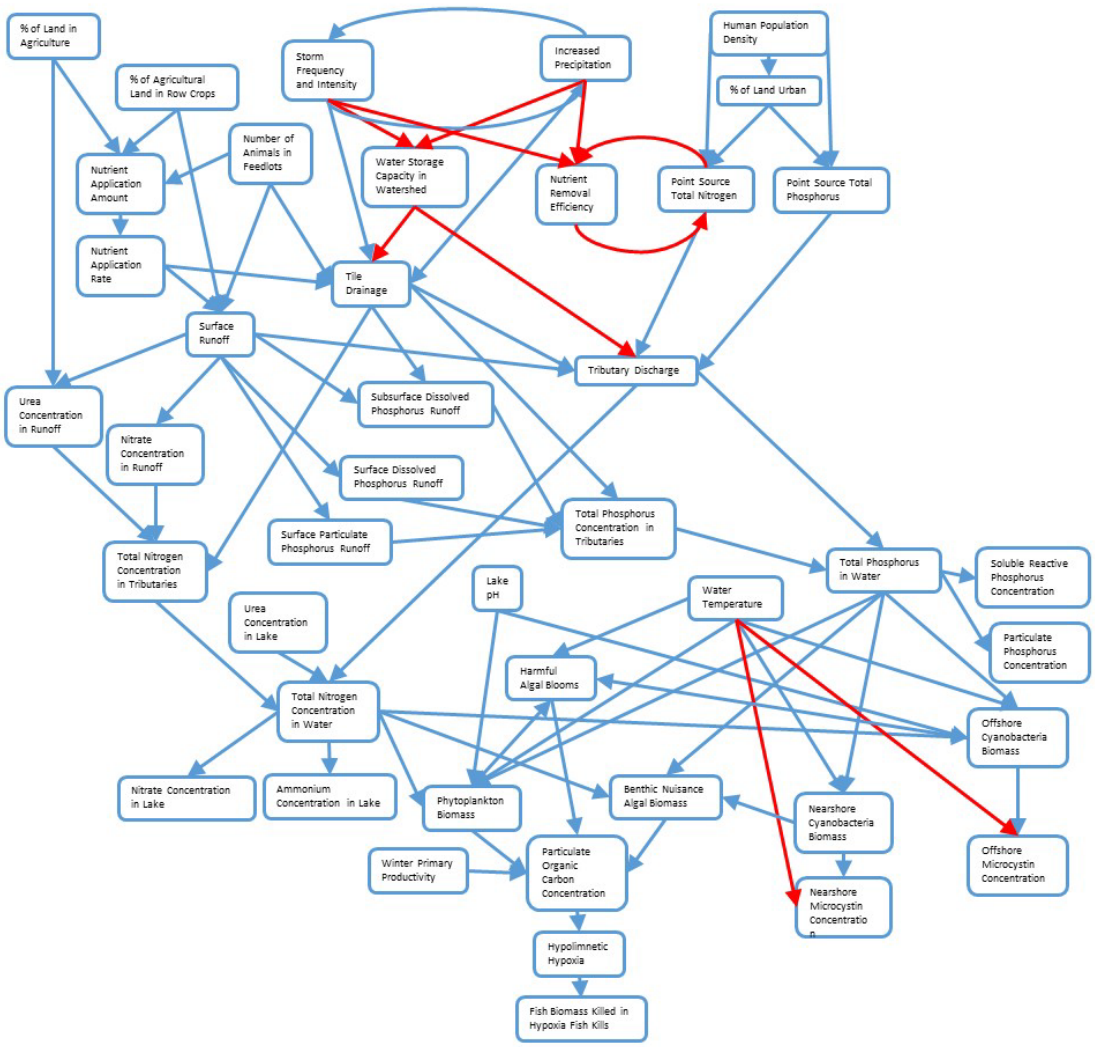

Figure 3: Fuzzy cognitive map created by Team 3. Positive relationships are denoted by blue arrows. Negative relationships are denoted by red arrows.

Team 4

Team 4 created the most detailed map of the workshop. Relationships that evoked a lot of discussion by team members were indicated with stars on the drawn map. The main eutrophication outcomes were hypoxia, HABs, and beach closures, with drivers being mostly climate or population concepts. Concepts were somewhat organized into categories, but the FCM was less modular than those of other teams.

Team 4's map had many terminal receivers (dead ends), and areas where more relationships could be added. For instance, in the FCM, lake pH was included as a concept but did not drive any other variables, yet this was discussed at length when the overall group reviewed Team 3's map. All workshop participants felt that seeing other teams' maps during the drawing phase could have informed their own map development.

Greenhouses were a mostly unknown concept, as Team 4 lacked the expertise in that area. They felt that greenhouses produce a high concentration but a small quantity of nutrients, especially as most of the water is recycled. It would be interesting to know the relative contribution of greenhouses as compared to traditional agriculture and feedlots.

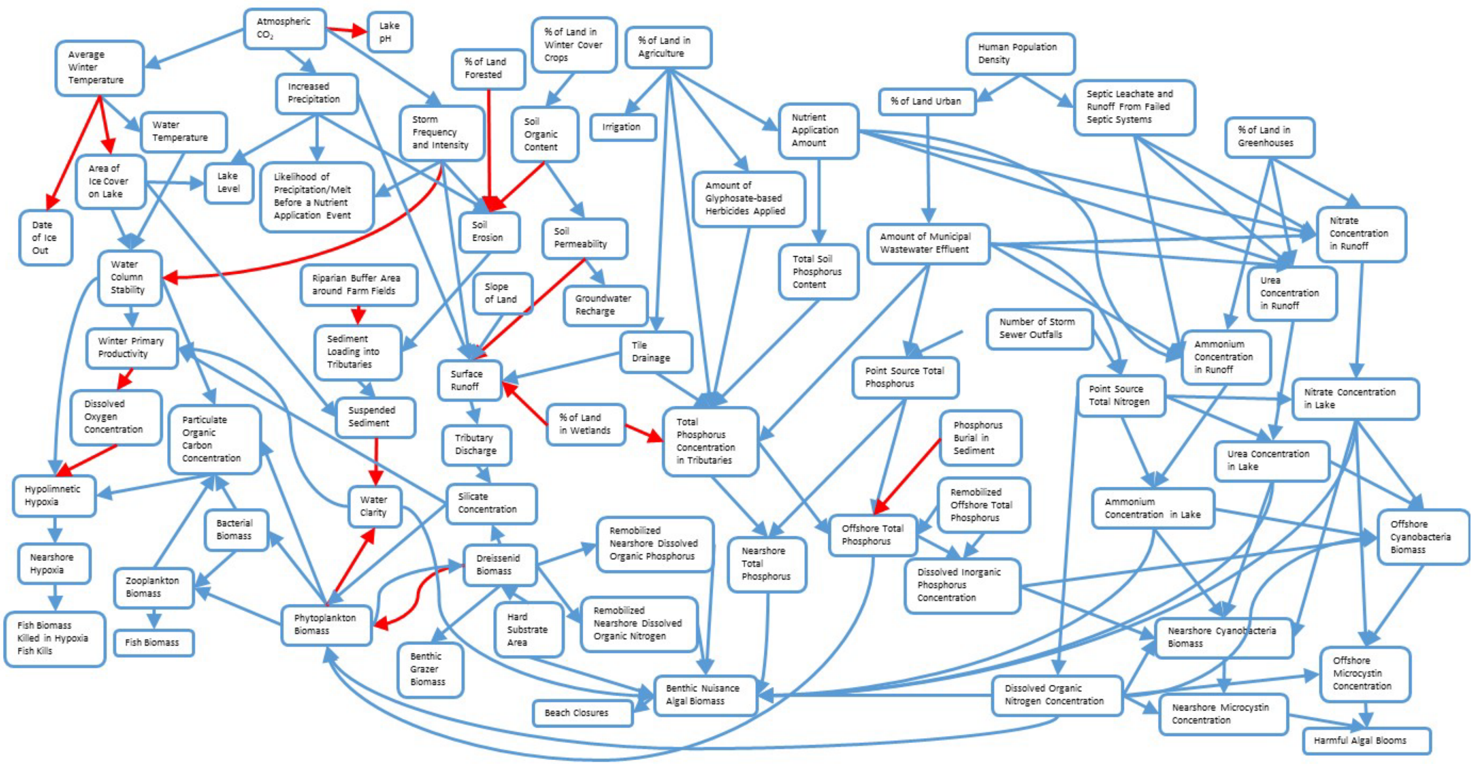

Figure 4: Fuzzy cognitive map created by Team 4. Positive relationships are denoted by blue arrows. Negative relationships are denoted by red arrows.

Consensual Map

The consensual map resulting from combining the four team maps contained 116 concepts and 382 relationships (Table 1) and could not be effectively illustrated due to the number of concepts and their interrelationships. Twelve concepts appeared on all four team maps (phytoplankton biomass, benthic nuisance algal biomass, tile drainage, offshore cyanobacteria biomass, nearshore cyanobacteria biomass, increased precipitation, HABs, water temperature, hypolimnetic hypoxia, nitrate concentration in lake, human population density, and offshore microcystin concentration; Table 2). Indegree, outdegree, centrality, and ubiquity scores for each concept are given in Table 2. A simplified version of the consensual map is given in Figure 5 using a slicing parameter. Relationships with absolute importance values greater than 0.25 (top quartile) are illustrated below, with any relationships in the bottom three quartiles (importance ≤ 0.25) removed. Importance values for each relationship were the mean non-zero values assigned to that relationship in breakout FCMs multiplied by the proportion of individual maps in which the relationship appeared (see Methods). This simplified consensual FCM shows 42 concepts and 36 relationships.

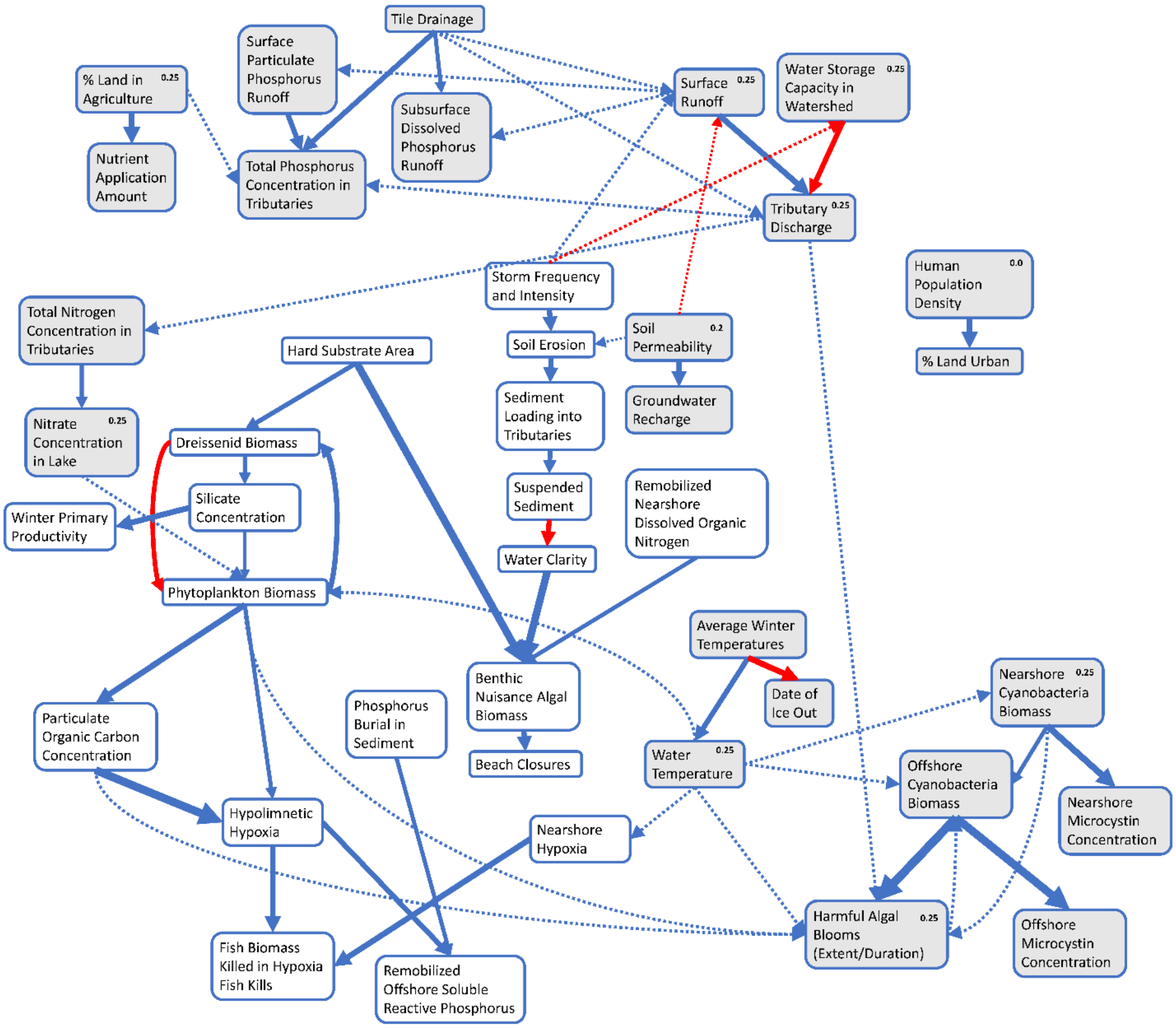

Figure 5: Simplified FCM depicting the top quartile of relationships (strength >0.25). Arrow width denotes relative relationship strength. Red arrows denote negative relationships and blue denote positive. Concepts that are greyed out are not connected to the main map when excluding relationships ≤ 0.25. Dashed arrows show the strongest relationships that would connect these greyed out concepts with the main map, and the strength of those dashed lines is given in the connected greyed concept.

Table 2: Indices for concepts appearing in the entire consensual FCM (not simplified). Outdegree refers to the absolute sum of strengths for relationships originating from the concept. Concepts with high outdegree may be important drivers of system dynamics. Indegree refers to the absolute sum of strengths for relationships influencing the concept. Concepts with high indegree may be good indicators of changes within the system. Centrality is indegree plus outdegree and gives an idea of a concept's relative importance in the map. Ubiquity is the number of team maps that on which a concept appeared (maximum 4). The table is organized from high to low centrality.

Concept	Outdegree	Indegree	Centrality	Ubiquity
Phytoplankton Biomass	2.5	4	6.5	4
Benthic Nuisance Algal Biomass	0.85	3.95	4.8	4
Offshore Cyanobacteria Biomass	1.8	2.55	4.35	4
Total Phosphorus Concentration in Tributaries	1.1	2.95	4.05	3
Tributary Discharge	1.7	2.25	3.95	3
Surface Runoff	1.75	1.95	3.7	2
Tile Drainage	2.5	1.1	3.6	4
Dreissenid Biomass	2.25	1.325	3.575	3
Nearshore Cyanobacteria Biomass	1.45	2.05	3.5	4
Amount of Municipal Wastewater Effluent	2.55	0.9	3.45	3
Harmful Algal Blooms (Extent/Duration)	0.75	2.45	3.2	4
Hypolimnetic Hypoxia	1.45	1.75	3.2	4
Increased Precipitation	2.35	0.5	2.85	4
Soil Erosion	0.8	1.9	2.7	2
Point Source Total Nitrogen	1.4	1.3	2.7	3
Inorganic Phosphorus Concentration in Tributaries	1.1	1.55	2.65	2
Storm Frequency and Intensity	2.2	0.4	2.6	3
Water Temperature	2.15	0.45	2.6	4
Particulate Organic Carbon Concentration	0.7	1.75	2.45	3
Nitrate Concentration in Lake	1.4	1	2.4	4
Total Nitrogen Concentration in Tributaries	0.95	1.45	2.4	3
Average Winter Temperatures	1.95	0.25	2.2	3
Discharge of Spent Irrigation Water from Greenhouses	1.6	0.5	2.1	2
Total Nitrogen Concentration in Water	1.4	0.7	2.1	1
Nutrient Application Amount	1.25	0.8	2.05	2
Total Soil Phosphorus Content	1.05	0.95	2	3
Nutrient Application Rate	1.05	0.9	1.95	3
Urea Concentration in Runoff	0.45	1.5	1.95	2
Point Source Total Phosphorus	0.75	1.15	1.9	3
Total Phosphorus in Water	1.45	0.45	1.9	1
Ammonium Concentration in Lake	1.1	0.75	1.85	3
Water Clarity	0.9	0.95	1.85	3
Particulate Phosphorus Concentration	0.575	1.25	1.825	2
Water Storage Capacity in Watershed	0.8	0.95	1.75	2
Human Population Density	1.7	0	1.7	4
Crop Yield	0.9	0.8	1.7	2
Nitrate Concentration in Runoff	0.45	1.25	1.7	2

Percentage of Land in Agriculture	1.65	0	1.65	3
Degree of Nutrient Incorporation into Soil	0.8	0.85	1.65	2
Nearshore Microcystin Concentration	0	1.65	1.65	3
Water Column Stability	0.9	0.7	1.6	2
Winter Primary Productivity	0.4	1.2	1.6	3
Silicate Concentration in Water	0.8	0.8	1.6	2
Urea Concentration in Lake	1.2	0.4	1.6	2
Offshore Microcystin Concentration	0.15	1.4	1.55	4
Soluble Reactive Phosphorus Concentration	0.75	0.8	1.55	2
Dissolved Inorganic Phosphorus Concentration in Lake	0.9	0.6	1.5	2
Phosphorus Solubility in Soil	0.65	0.8	1.45	2
Remobilized Offshore Soluble Reactive Phosphorus	0.4	1.05	1.45	2
Soil Permeability	0.85	0.55	1.4	2
Suspended Sediment	0.6	0.8	1.4	2
Percentage of Land in Greenhouses	1.25	0.15	1.4	2
Dissolved Organic Nitrogen Concentration in Lake	0.95	0.45	1.4	2
Subsurface Dissolved Phosphorus Runoff	0.45	0.9	1.35	2
Surface Dissolved Phosphorus Runoff	0.45	0.9	1.35	2
Sediment Loading into Tributaries	0.4	0.9	1.3	2
Nearshore Hypoxia	0.5	0.8	1.3	2
Ammonium Concentration in Runoff	0.2	1	1.2	1
Phosphorus Burial in Sediment	0.6	0.55	1.15	3
Surface Particulate Phosphorus Runoff	0.45	0.65	1.1	2
Nutrient Removal Efficiency	0.4	0.7	1.1	2
Offshore Total Phosphorus	0.5	0.6	1.1	1
Hard Substrate Area	1.05	0	1.05	3
Percentage of Agricultural Land in Row Crops	0.6	0.4	1	2
Organic Phosphorus Concentration in Tributaries	0.15	0.85	1	1
Fish Biomass Killed in Hypoxia Fish Kills	0	1	1	3
Percentage of Land Urban	0.5	0.5	1	2
Bacterial Biomass	0.65	0.3	0.95	2
Zooplankton Biomass	0.55	0.4	0.95	2
Septic Leachate and Runoff from Failed Septic Systems	0.75	0.2	0.95	1
Non-growing Season Runoff	0.2	0.7	0.9	1
Percentage of Land in Winter Cover Crops	0.9	0	0.9	3
Date of Ice Out	0.4	0.5	0.9	2
Remobilized Nearshore Dissolved Organic Nitrogen	0.55	0.3	0.85	2
Subsurface Particulate Phosphorus Runoff	0.35	0.45	0.8	1
Area of Ice Cover on Lake	0.55	0.25	0.8	1
Soil Phosphorus Stratification	0.5	0.25	0.75	1
Irrigation	0.4	0.35	0.75	2
Beach Closures	0	0.7	0.7	3
Amount of Glyphosate-based Herbicides Applied	0.3	0.4	0.7	2
Nutrient Application Rate x Increased Precipitation	0.2	0.5	0.7	1

Atmospheric CO_2	0.7	0	0.7	1
Groundwater Recharge	0.1	0.5	0.6	2
Percentage of Landscape in Wetlands	0.6	0	0.6	2
Nearshore Soluble Reactive Phosphorus	0.4	0.2	0.6	1
Soil Organic Content	0.35	0.2	0.55	1
Nearshore Total Phosphorus	0.2	0.35	0.55	1
Dissolved Phosphorus Concentration in Tributaries	0	0.5	0.5	1
Denitrification	0	0.5	0.5	1
Nearshore Autochthonous Particulate Organic Carbon	0.3	0.2	0.5	1
Likelihood of Precipitation Melt Before a Nutrient Application Event	0	0.5	0.5	1
Percentage of Landscape Forested	0.45	0	0.45	2
Number of Animals in Feedlots	0.45	0	0.45	2
Soil Phosphorus Desorption	0.25	0.2	0.45	1
Temperature at Time of Nutrient Application in Agriculture	0.3	0.1	0.4	1
Optimization of Sewage Treatment Plant Operations	0.4	0	0.4	2
Area of Rented Land	0.2	0.2	0.4	1
Percentage of Nutrients Recovered from Spent Irrigation Water from Greenhouses	0.2	0.2	0.4	1
Lake Level	0	0.4	0.4	1
Dissolved Oxygen Concentration	0.25	0.15	0.4	1
Hydrological Connectivity	0.15	0.2	0.35	1
Percentage of Agricultural Land in No Till	0.35	0	0.35	1
Lake pH	0.3	0.05	0.35	2
Remobilized Nearshore Total Phosphorus	0.15	0.2	0.35	1
Instream and Bank Erosion	0.2	0.1	0.3	1
Overflows of Combined Storm and Sanitary Sewers	0.2	0.1	0.3	1
Particulate Phosphorus Concentration in Tributaries	0	0.3	0.3	1
Remobilized Nearshore Soluble Reactive Phosphorus	0.2	0.1	0.3	1
Number of Storm Sewer Outfalls	0.3	0	0.3	1
Remobilized Nearshore Dissolved Organic Carbon	0.15	0.1	0.25	1
Riparian Buffer Area Around Farm Fields	0.25	0	0.25	1
Slope of Land	0.2	0	0.2	1
Remobilized Offshore Total Phosphorus	0.2	0	0.2	1
Fish Biomass	0	0.2	0.2	1
Benthic Grazer Biomass	0	0.2	0.2	1
Amount of Legacy Phosphorus Released from Wetlands or Floodplains	0.05	0.05	0.1	1

Discussion

General workshop discussion

There was a strong consensus among groups on what eutrophication 'is' (i.e., the key manifestations of eutrophication) and what the ultimate drivers of eutrophication are. The differences among groups arose in the pathways used to describe the link between the ultimate drivers and the manifestations of eutrophication. Examining the differences among teams and with respect to the consensual FCM created in the 2009 workshop could lead to some hypothesis driven work.

As is the case with any modeling exercise, once the ultimate drivers are identified, one must ask whether the drivers can be influenced by management actions, or do they have solely predictive value. The other question that emerges concerns modelling error, whether it is errors in the connections, errors in the slicing parameter that led to the simplified, consensual map or the limitations of the method itself. For example, seeing soluble phosphorus concentration ranked lower than particulate and total phosphorus concentration was a surprising outcome as was the disconnected map segment for harmful algal blooms. This might reflect the capacity for measurement and would be in line with the discussion below on loads versus concentrations

Several groups discussed whether nutrient concepts that specified concentrations should be modified to refer to loadings instead. An argument in favor of focusing on loadings is that loadings can be measured, and can theoretically be regulated with a goal of achieving target levels through changes in land management. For example, Annex 4 of the 2012 Protocol for the Great Lakes Water Quality Agreement (GLWQA; United States and Canada 2012) calls on the parties to set phosphorus load reduction targets among the parties to achieve ecosystem objectives related to eutrophication symptoms. This led to the GLWQA Annex 4 recommendation that phosphorus loadings from priority tributaries be reduced (details given at https://www.epa.gov/glwqa/recommended-binational-phosphorus-targets). Consequently, recent eutrophication modeling efforts (e.g., Scavia et al. 2016) incorporate nutrient loadings to ensure they can be used in the GLWQA annual assessments of nutrient management. Thus, expressing nutrients in terms of loadings facilitates regulation and simplifies compliance monitoring and modeling efforts. Furthermore, from a monitoring perspective, it is easier to measure whole lake loadings than in-lake concentrations. However, biological processes are determined by nutrient concentrations. Concentrations reflect the conditions experienced by biota, and so are a better predictor of algal response to changes in drivers and stressors.

Workshop discussion of specific concepts/relationships

There was some discussion around the relationship between silica and phytoplankton biomass. Does the amount of silica affect phytoplankton biomass, or just community composition? Silica is a limiting element necessary to support diatoms. In the absence of enough silica, other types of phytoplankton may compensate so that the net biomass in unaffected.

Participants discussed winter limnology at length. A winter diatom bloom forms under ice in January/February and does not involve spring convection. There could be some convective mixing, but this would only occur when there is snow-free ice. Lake Erie has a long fetch, and as a result of prevailing winds does have a lot of snow-free ice. Unfortunately, winter samples are collected from icebreakers, so the structure is disturbed in the process of collecting the samples. However, diatoms are thought to be attached to the undersurface of the ice. In the central basin, there is a similar biomass of algae in the winter as in the summer and with diatoms dominating the winter community, silica is depleted from the water column. Further, a temporal disconnect between phytoplankton production and bacterial remineralization means that much of the diatom production that is exported to the benthos during spring accumulates on the sediment surface rather than being decomposed.

Team 3 included a link between pH and phytoplankton biomass, because they argued that high pH affects dissolved carbon, which selects for cyanobacteria. Above certain pH levels diatoms are unable to absorb silica. Cyanobacteria drive up the pH, making carbon less available to the rest of the algal community. Previously, effects of HABs have possibly been dampened due to low pH caused by acid rain. However, one can observe variations in pH of up to 0.5 units over an afternoon, all driven by biological activity.

Areas for future focus

One of the strengths of this method of model building is that it promotes discussion around knowledge gaps. Extensive discussion around winter limnology led participants to suggest that this topic could benefit from additional work. During general discussions, workshop participants identified two other areas of uncertainty that are potentially important to the discussion of eutrophication: the growing greenhouse industry, and social factors affecting land-based concepts (e.g., decision-making around use of best management practices (BMPs)). Several concepts related to greenhouses were included in the workshop concept list, but several breakout teams said that they lacked the expertise necessary to show how greenhouses influence eutrophication. This may be a true knowledge gap, or it may reflect a gap in invited expertise at the workshop. Regardless, the greenhouse industry is growing and understanding its effects on nutrient loading and eutrophication warrants additional study.

Socio-economic factors that contribute to land-based concepts is a broad topic. It was outside the scope of this FCM exercise as the concepts were not available. However, understanding the social aspects of such features as BMP adoption is critical for translating an understanding of factors driving eutrophication into policy that allows management of those features. Some work has been done on this (e.g., Liu, Bruins, and Heberling 2018; Akkari and Robin Bryant 2017; Smith et al. 2019).

Consensual FCM

The 12 concepts that were used by all four teams demonstrate that they are generally agreed upon as important to the consideration of eutrophication in Lake Erie. These 12 concepts can be broken down into several categories: biological manifestations (phytoplankton biomass, benthic nuisance algal biomass, offshore cyanobacteria biomass, nearshore cyanobacteria biomass, HABs, and offshore microcystin concentration), abiotic manifestations (hypolimnetic hypoxia), climate factors (increased precipitation, water temperature), human factors (human population density), and intermediary factors (tile drainage, nitrate concentration in lake). The fact that biological manifestations make up the majority of the concepts that were included by all teams is logical, as these manifestations are what drive our desire to address eutrophication. Notably, the eutrophication response indicators (ERIs) identified through the GLWQA Annex 4 - phytoplankton biomass, western basin cyanobacteria biomass, central basin hypoxia, and *Cladophora* (benthic nuisance algae) biomass – are all included in the 12 concepts used by all teams. This indicates a high degree of consensus on what eutrophication 'is', considering that the concept itself is a latent variable. All the ERIs, with the exception of hypoxia, are also included in the list of potential indicators derived from this workshop, discussed further below.

Potentially important drivers may be those concepts with high influence on other concepts (i.e., high outdegree). The five concepts with the highest outdegree were:

1. Amount of municipal wastewater effluent
2. Phytoplankton biomass
3. Tile drainage
4. Increased precipitation
5. Dreissenid biomass

Increased precipitation is climate-related and unfeasible to manage to control eutrophication although impacts such as stormwater runoff in urban areas can be managed with a range of BMPs. However, the concept with the highest outdegree, amount of municipal wastewater effluent, which was included in three team maps (Table 2), is well within the realm of management. Phytoplankton biomass is an unexpected concept for inclusion in a list of potential drivers, but its presence is likely due to its importance to the discussion of eutrophication in general. While it has a high outdegree (2.5), it has a higher indegree (4.0), and was found on all four breakout team maps, and is revisited in the indegree discussion below. Dreissenid biomass is not an unexpected driver, especially for nearshore eutrophication (Hecky et al. 2004), but one that is not very amenable to management. Tile drainage was not explicitly defined, and in retrospect it was determined that some groups interpreted it to be 'area of land drained by tile drains' while others interpreted it as 'amount of nutrients moving though tile drains'. Thus, this concept was too ambiguous for useful interpretation.

Potentially important integrators or indicators may be those concepts that are heavily influenced by other concepts in the FCM (i.e., high indegree). The five concepts with the highest indegree were:

1. Phytoplankton biomass
2. Benthic nuisance algal biomass
3. Total phosphorus concentration in tributaries
4. Offshore cyanobacteria biomass
5. Harmful algal blooms

Of these, nearly all are related to the visual manifestations of eutrophication that are already in the public awareness. Four of these top five potential indicators relate directly to Annex 4's ERIs (with offshore cyanobacteria biomass and harmful algal blooms both relating to the 'western basin cyanobacteria biomass' ERI). The exception is total phosphorus concentration in tributaries, which is an intermediary concept linking on-land concepts with in-lake concepts. The high indegree of total phosphorus concentration in tributaries is likely due to its key position linking the flow of phosphorus from land-based concepts to lake-based concepts through the tributaries.

One critical issue with the simplified visualization of the consensual FCM (Figure 5) was the lack of a clear connection between phosphorus and the potential eutrophication indicators. Phosphorus is a well-recognised driver of eutrophication (United States and Canada 2012; Scavia et al. 2016). In retrospect, this was a by-product of how the workshop concept list was created, by asking participants to suggest concepts they felt would be important. The final concept list contained 37 different concepts that referred to phosphorus in some context or form. This reflects how important participants felt phosphorus was to the maps, but it also resulted in a dilution effect on the importance of each phosphorus concept in the final consensual FCM. As different groups focused on different forms and aspects of phosphorus (e.g., a group that wanted to simplify their map may use total phosphorus in water, whereas a group interested in spatial differences may use nearshore total phosphorus and offshore total phosphorus), the importance of any one phosphorus concept was lessened. This issue could be addressed by being more strategic about the development of the initial concept list.

Participant Feedback

At the workshop

Participants were asked if another workshop was to be conducted, what would confer the most benefit: a second workshop with the same type of participants to increase sample size, or a workshop that expands the perspectives in play, such as a stakeholder workshop. Participants liked the idea of contrasting the results of this workshop with a stakeholder workshop, which may give us insight into where stakeholder concerns really are, showing us where we should focus our efforts. To make progress in addressing eutrophication, we need to understand why people make the decisions they make. It would also be valuable to separately involve stakeholders from each country, and stakeholders of varying perspectives (fishers, farmers, interested public, etc.). In a similar vein, it would be interesting to do this exercise with a college class, as part of a limnology class or similar. It would create a lot of data and provide a good learning opportunity to the students.

This workshop grouped participants into broad breakout groups, attempting to replicate the breadth of expertise within each group. In future workshops, it may be beneficial to group participants by expertise, so that each breakout group can focus in closely on their area of expertise, and create a more solid, but focused, FCM. In this way, maps from a similar group of experts may be combined and maps representing separate areas of expertise would be equally counted. This would allow results to truly represent consensus, rather than having team members defer to whomever has the most expertise. If feasible, we could get the best of both worlds by spending one day working in broad groups, and the other day working in expertise-based groups.

Some participants felt the workshop was valuable for bringing people together but were unsure about the actual value of data recorded in the FCMs. The intangible outcomes of the workshop may be more valuable than the tangible outcomes. However, there may be a way of harvesting more data from the group. We could look into making the modeling exercise more quantitative and consider the actual workshop as the *a priori* exercise. We could come back to the group with a way of going through the linkages in a systematic way. Paul was interested in boiling the FCM exercise down into a format that could be completed electronically to send out to a larger group. This might involve using the consensual map arising from this workshop and soliciting critiques.

It would also be valuable to involve more economists and sociologists in future work. We could identify the ways in which costs/price and social factors drives decisions on the land that increase or decrease nutrient loads. Using the FCM we could identify areas where we are most certain of the connections between concepts we can control and manifestations of eutrophication. We could then prioritize the areas that have a high response to changing price signals, do not require large amount of social change and high certainty. Regardless of the socioeconomics angle, reaching consensus on areas of high uncertainty would be a great benefit for managing this issue.

Follow-up e-survey

A follow-up e-survey was distributed to participants after the workshop. Nine people responded and were overall positive about the experience and the method. The respondents were evenly split between those who were not at all familiar with FCMs before the workshop (4), and those who were somewhat familiar (4), with one person in the middle who was not so familiar. The most cited beneficial parts of the workshop were the opportunity to have discussions with other experts from outside of the participant's field, and the opportunity to learn about FCMs as a tool. The part of the workshop that was deemed least important was the discussion about whether terms should be included with the larger group. Overall, people felt that the whole group was engaged and interested, and felt that this made for a valuable experience. They were hopeful that a tangible product could come out of the work.

Respondents had several suggestions for improvement for future workshops:

- Include FCMs from previous workshops in the briefing materials.
- Take formal breaks to check in with the other groups to see how they are approaching the problem.
- Be clearer from the beginning about the goal of the exercise (whether it is to come up with the most thorough map, or a simple map).
- Have additional ways to weight map elements (e.g., uncertainty, importance to overall issue)
- Allow more time for the entire group to discuss ("argue" and "defend") linkages, and then allow changes to be made to the individual maps. This would allow the final map to represent more of a consensus.
- Some type of two-stage workshop, which may involve:
    - A 'shuffling' of participants at the end, where experts focus in on their areas of expertise to assign weights.
    - Breaking out into topic-specific groups at some point in the process to give more robustness to each section.
    - Using the first stage to create a broad strokes map, where main sections of the map are identified, followed by more focused maps of each section with finer-scale concepts.
- Being more strategic in the development of the concept list, to avoid issues of 'concept dilution' as was seen with phosphorus in the current workshop.

Next Steps

Conference Poster

A conference poster was developed and presented at the International Association for Great Lakes Research (IAGLR) conference in Brockport, NY, in June 2019.

Manuscript

Interested participants will work to develop a manuscript, following the creation of the consensual FCM. This manuscript may focus on one or more of the following:

- Comparing the new version of the consensual FCM with that produced in the 2009-2014 workshops. It would be interesting to see how our basic understanding may have changed or how specialized areas of focus, such as the urban flow, were captured in a more general exercise.
- Uncertainty within the consensual FCM, i.e. a methodological discussion.
- Providing a conceptual map to help guide the adaptive management process. The FCM could provide a communication tool for discussing adaptive management by showing the complexity of the system, the main paths by which nutrients move from the land into the lake, and the impact of managing certain drivers to affect the manifestations of eutrophication.

Other follow-up activities

A potential follow-up activity could be to do a similar workshop at the 2020 IAGLR conference, which will be held in Winnipeg. The workshop could focus on Lake Winnipeg, which has similar eutrophication issues, and the resultant FCMs could be compared. However, we would need to think about what finding similarities or differences would mean in the context of this work.

As discussed in the Participant Feedback section, expanding this exercise to be included in a university class may produce interesting results, as well as provide a valuable learning experience for students. We will investigate the logistics of modifying the FCM exercise to fit with the goals of an undergraduate or graduate course setting.

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Appendix 1: Participant Information

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Ngan Diep*
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**participated remotely on Day 1, did not participate in Day 2*

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Appendix 2: Concept List Provided to Participants

Concept #	Concept	Concept used in Consensual FCM?
1	Average Winter Temperatures	Y
2	Frequency of Intermittent Pulse Exposures	
3	Increased Precipitation	Y
4	Storm Frequency and Intensity	Y
5	Surface Runoff	Y
6	Subsurface Particulate Phosphorus Runoff	
7	Subsurface Dissolved Phosphorus Runoff	Y
8	Surface Particulate Phosphorus Runoff	Y
9	Surface Dissolved Phosphorus Runoff	Y
10	Ammonium Concentration in Runoff	Y
11	Nitrate Concentration in Runoff	Y
12	Non-growing Season Runoff	Y
13	Urea Concentration in Runoff	Y
14	Sediment Loading into Tributaries	Y
15	Total Phosphorus Concentration in Tributaries	Y
16	Inorganic Phosphorus Concentration in Tributaries	Y
17	Organic Phosphorus Concentration in Tributaries	Y
18	Soil Erosion	Y
19	Soil Organic Content	Y
20	Soil Permeability	Y
21	Soil Phosphorus Desorption	Y
22	Soil Phosphorus Stratification	Y
23	Total Soil Phosphorus Content	Y
24	Total Soil Organic Carbon Content	
25	Phosphorus Solubility in Soil	Y
26	Tributary Discharge	Y
27	Amount of Legacy Phosphorus Released from Wetlands or Floodplains	Y
28	Groundwater Recharge	Y
29	Human Population Density	Y
30	Hydrological Connectivity	Y
31	Slope of Land	Y
32	Instream and Bank Erosion	Y
33	Nutrient Removal Efficiency	Y
34	Percentage of Land Urban	Y
35	Percentage of Land in Winter Cover Crops	Y
36	Percentage of Landscape Forested	Y

37	Percentage of Non-Agriculture Land Vegetated	
38	Percentage of Non-Agriculture Land with Green Infrastructure	
39	Percentage of Land in Agriculture	Y
40	Percentage of Landscape in Wetlands	Y
41	Percentage of Land with Permanent Cover	
42	Percentage of Land in Greenhouses	Y
43	Regulated Farm Land	
44	Percentage of Agricultural Land in No-Till	Y
45	Percentage of Agricultural Land Cropped Annually	
46	Percentage of Agricultural Land in Row Crops	Y
47	Area of Rented Land	Y
48	Likelihood of Precipitation/Melt Before a Nutrient Application Event	Y
49	Number of Animals in Feedlots	Y
50	Percentage Manure Diverted to Biogas Digestion	
51	Percentage Manure Diverted to Other Areas of Need	
52	Percentage Phosphorus Recovered from Rural Non-point Sources	
53	Crop Yield	Y
54	Degree of Nutrient Incorporation into Soil	Y
55	Nutrient Application Amount	Y
56	Nutrient Application Rate	Y
57	Riparian Buffer Area Around Farm Fields	Y
58	Tile Drainage	Y
59	Irrigation	Y
60	Amount of Glyphosate-based Herbicides Applied	Y
61	Area of Land Where Farmers Practice Crop Rotation	
62	Discharge of Spent Irrigation Water from Greenhouses	Y
63	Percentage of Nutrients Recovered from Spent Irrigation Water from Greenhouses	Y
64	Temperature at Time of Nutrient Application in Agriculture	Y
65	Percentage Phosphorus Recovered from Urban Non-point Sources	
66	Percentage Phosphorus Recovered from Urban Point Sources	
67	Adoption of Septic System Best Practices	
68	Number of Storm Sewer Outfalls	Y
69	Optimization of Sewage Treatment Plant Operations	Y
70	Overflows of Combined Storm and Sanitary Sewers	Y
71	Public Education on Eutrophication Issues	
72	Number of Retention Ponds in Use	
73	Septic Leachate and Runoff From Failed Septic Systems	Y
74	Amount of Industrial Wastewater Effluent	
75	Amount of Municipal Wastewater Effluent	Y

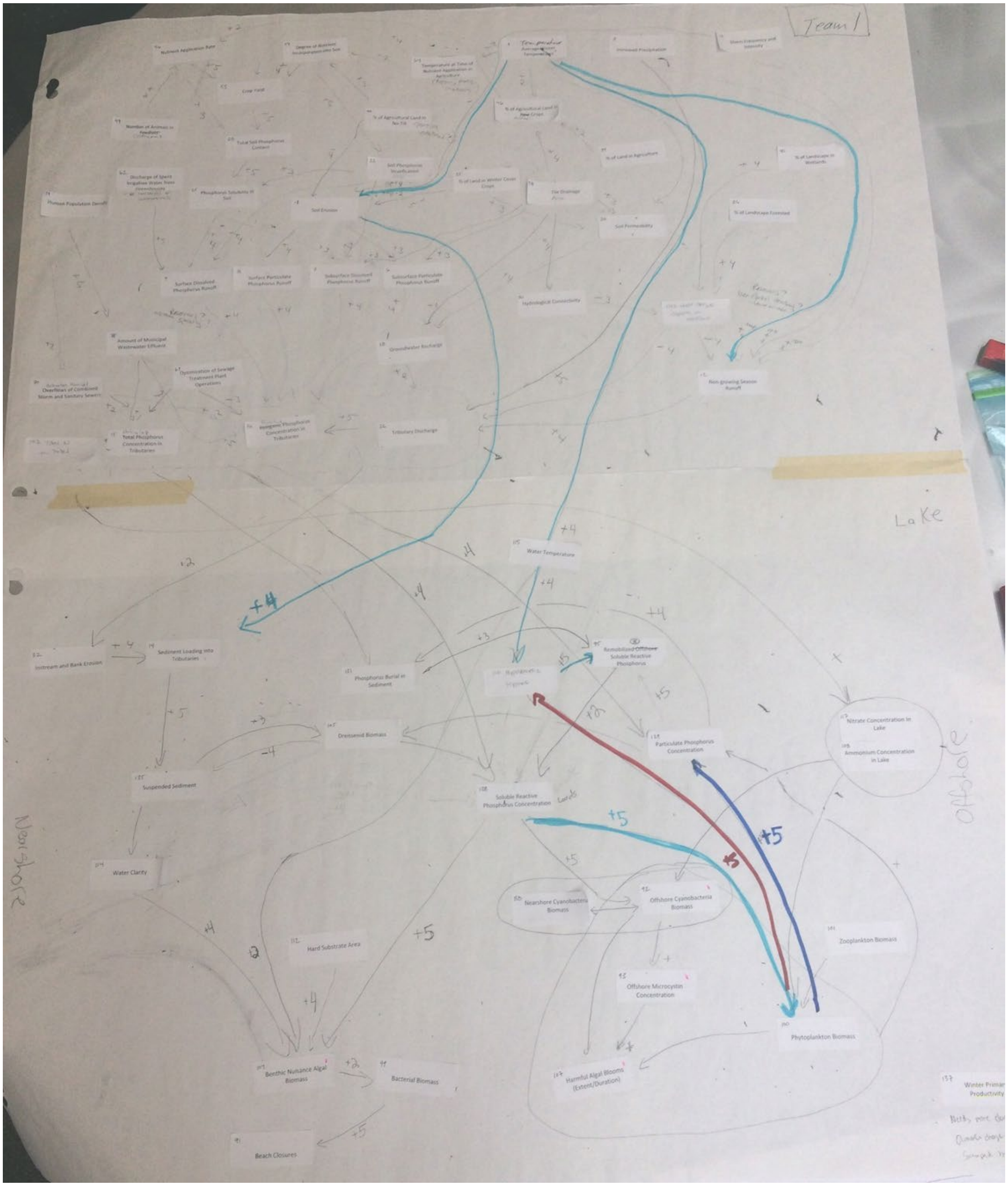
76	Dredge Spoil Disposal	
77	Percentage Municipal Solid Waste Converted to Biofuel	
78	Nearshore Allochthonous Dissolved Organic Carbon	
79	Nearshore Allochthonous Particulate Organic Carbon	
80	Nearshore Soluble Reactive Phosphorus	Y
81	Nearshore Total Phosphorus	Y
82	Remobilized Nearshore Dissolved Organic Carbon	Y
83	Remobilized Nearshore Dissolved Organic Nitrogen	Y
84	Remobilized Nearshore Particulate Phosphorus	
85	Remobilized Nearshore Soluble Reactive Phosphorus	Y
86	Remobilized Nearshore Total Phosphorus	Y
87	Shoreline Development	
88	Nearshore Cyanobacteria Biomass	Y
89	Nearshore Hypoxia	Y
90	Nearshore Microcystin Concentration	Y
91	Beach Closures	Y
92	Offshore Cyanobacteria Biomass	Y
93	Offshore Microcystin Concentration	Y
94	Remobilized Offshore Particulate Phosphorus	
95	Remobilized Offshore Soluble Reactive Phosphorus	Y
96	Remobilized Offshore Total Phosphorus	Y
97	Offshore Soluble Reactive Phosphorus	
98	Offshore Total Phosphorus	Y
99	Bacterial Biomass	Y
100	Phytoplankton Biomass	Y
101	Zooplankton Biomass	Y
102	Fish Biomass	Y
103	Benthic Grazer Biomass	Y
104	Benthic Nuisance Algal Biomass	Y
105	Dreissenid Biomass	Y
106	Fish Biomass Killed in Hypoxia Fish Kills	Y
107	Harmful Algal Blooms (Extent/Duration)	Y
108	Ammonium Concentration in Lake	Y
109	Area of Ice Cover on Lake	Y
110	Date of Ice Out	Y
111	Water Column Stability	Y
112	Hard Substrate Area	Y
113	Lake Level	Y
114	Water Clarity	Y

115	Water Temperature	Y
116	Lake pH	Y
117	Nitrate Concentration in Lake	Y
118	Urea Concentration in Lake	Y
119	Dissolved Oxygen Concentration	Y
120	Dissolved Inorganic Phosphorus Concentration in Lake	Y
121	Dissolved Organic Nitrogen Concentration in Lake	Y
122	Non-point Dissolved Organic Nitrogen	
123	Non-point Particulate Phosphorus	
124	Non-point Soluble Reactive Phosphorus	
125	Non-point Source Total Nitrogen	
126	Non-point Total Carbon	
127	Non-point Total Phosphorus	
128	Soluble Reactive Phosphorus Concentration	Y
129	Particulate Phosphorus Concentration	Y
130	Particulate Organic Carbon Concentration	Y
131	Phosphorus Burial in Sediment	Y
132	Point Source Soluble Reactive Phosphorus	
133	Point Source Total Nitrogen	Y
134	Point Source Total Phosphorus	Y
135	Suspended Sediment	Y
136	Total Phosphorus in Water	Y
137	Winter Primary Productivity	Y
138	Silicate Concentration in Water	Y
139	Crop Nutrient Retentive Ability Through Surface Cover	
140	Surface Phosphorus Runoff	
141	Hypolimnetic Hypoxia	Y
142	Total Nitrogen Concentration in Tributaries*	Y
143	Water Storage Capacity in Watershed*	Y
144	Atmospheric CO2*	Y
145	In-lake N:P*	
146	Denitrification*	Y
147	Total Nitrogen Concentration in Water*	Y
148	Nearshore Autochthonous POC*	Y
149	Dissolved Phosphorus Concentration in Tributaries*	Y
150	Particulate Phosphorus Concentration in Tributaries*	Y

**Concept was added to the list of available concepts during the workshop*

Appendix 3: Hard Copy FCMs Created in Workshop

Team 1:


Team 1
Lake
Nearshore
Offshore
Water Temperature
Phytoplankton Biomass
Zooplankton Biomass
Beach Closures
Bacterial Biomass
Water Clarity
Suspended Sediment
Dreissenid Biomass
Hard Substrate Area

Team 2:

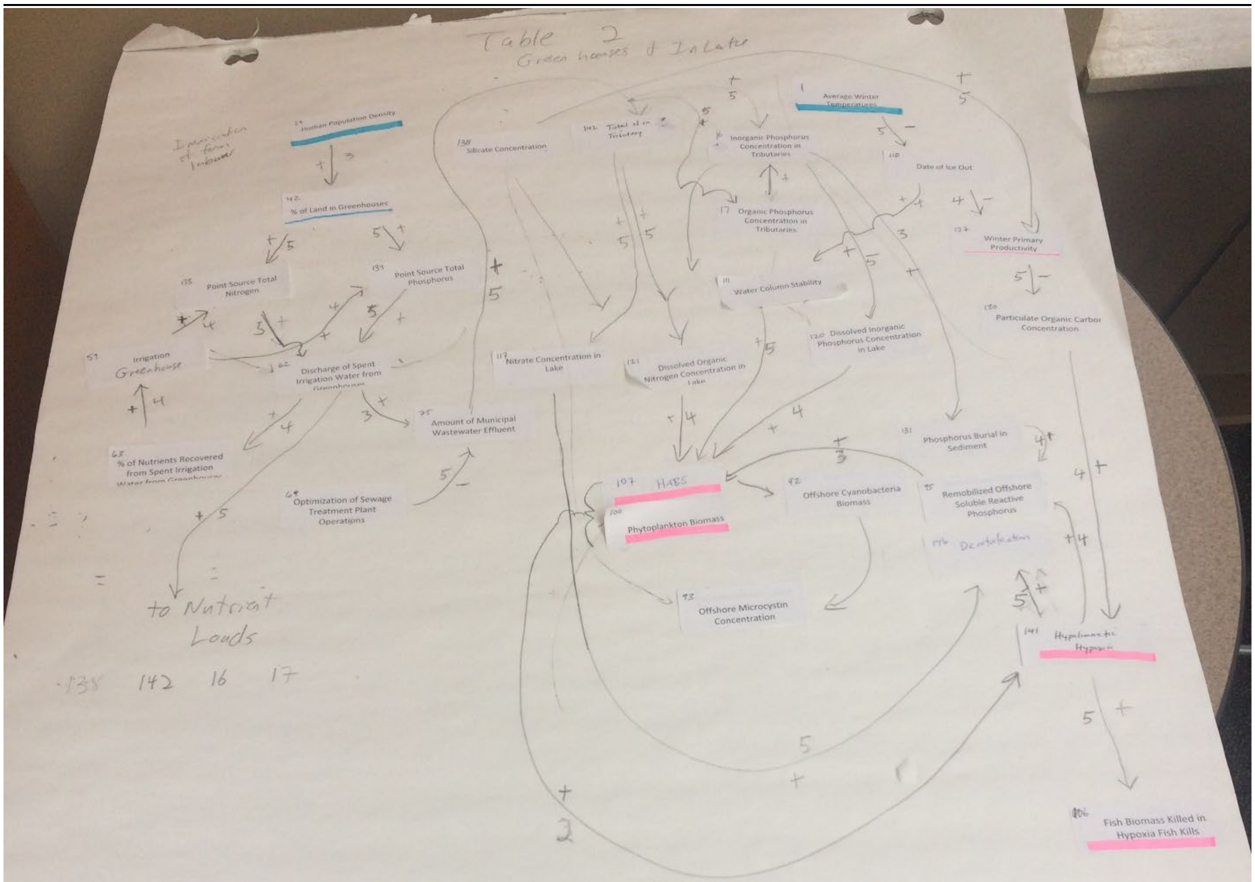
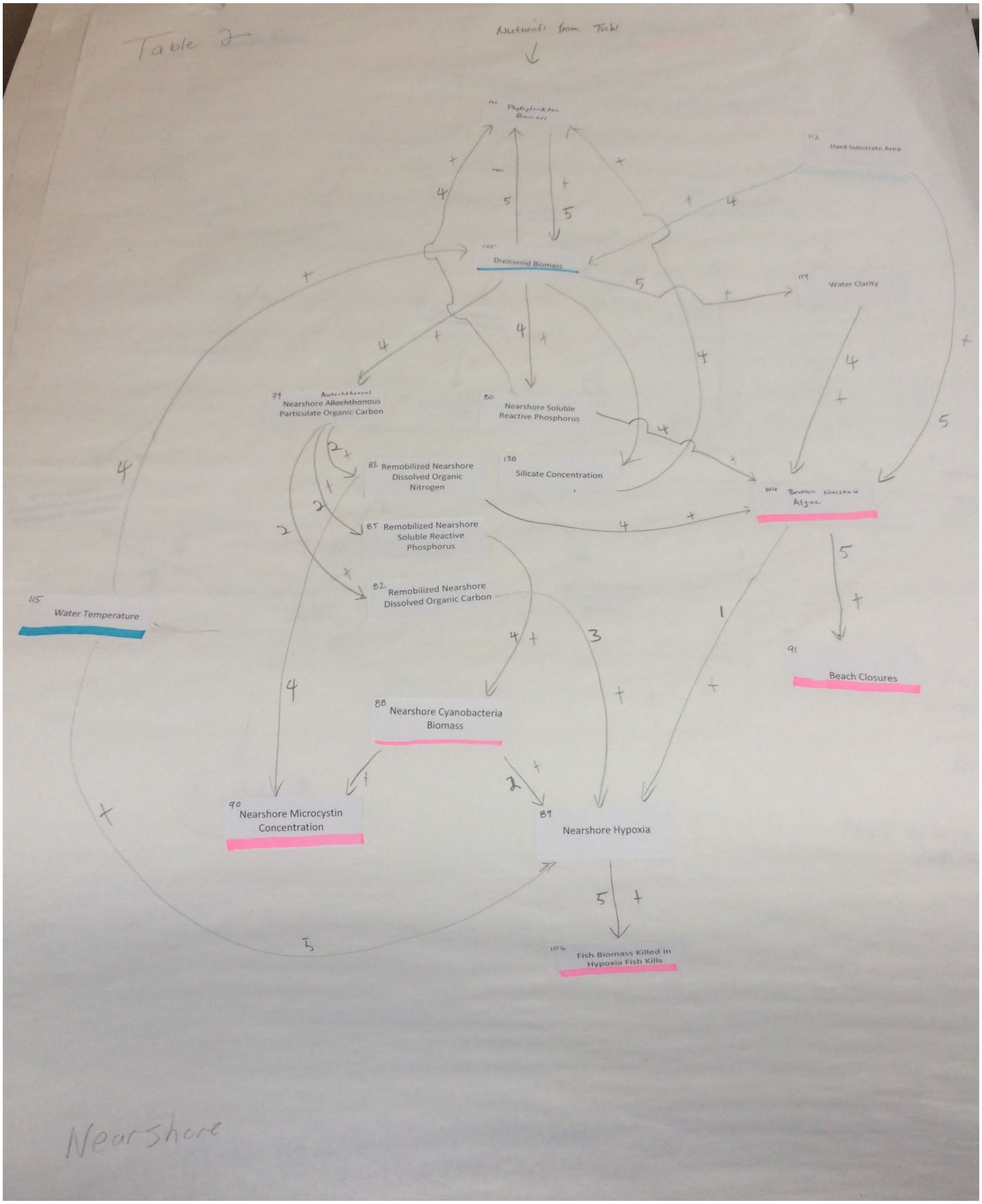
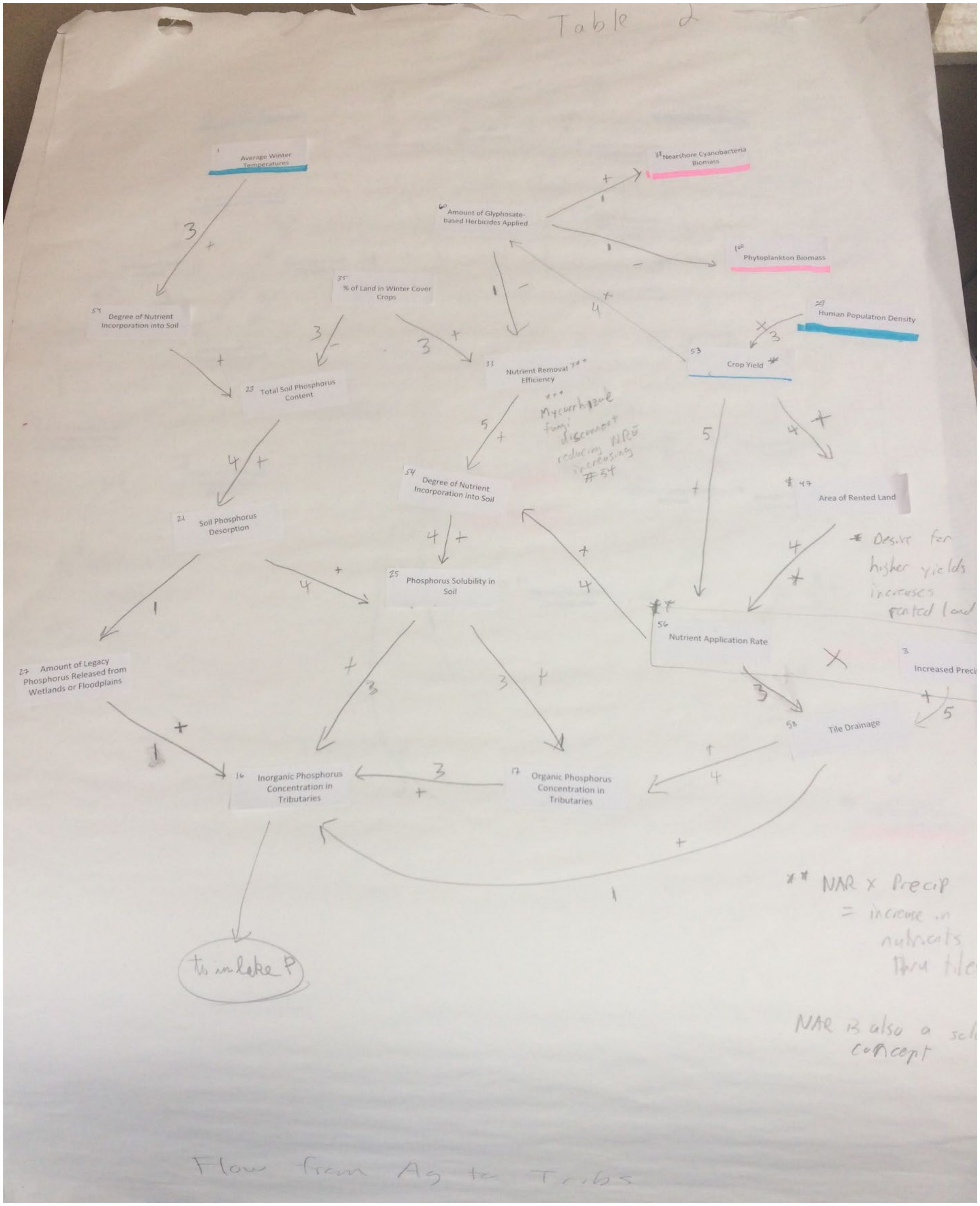


Table 2
Human Population Density
Silicate Concentration
Average Winter Temperatures
Inorganic Phosphorus Concentration in Tributaries
Date of Ice Out
% of Land in Greenhouses
Organic Phosphorus Concentration in Tributaries
Winter Primary Productivity
Point Source Total Nitrogen
Point Source Total Phosphorus
Water Column Stability
Particulate Organic Carbon Concentration
Irrigation
Greenhouse
Discharge of Spent Irrigation Water from Greenhouses
Nitrate Concentration in Lake
Dissolved Organic Nitrogen Concentration in Lake
Dissolved Inorganic Phosphorus Concentration in Lake
Amount of Municipal Wastewater Effluent
Phosphorus Burial in Sediment
% of Nutrients Recovered from Spent Irrigation
Optimization of Sewage Treatment Plant Operations
HABS
Phytoplankton Biomass
Offshore Cyanobacteria Biomass
Remobilized Offshore Soluble Reactive Phosphorus
Offshore Microcystin Concentration
to Nutrient Loads
142 16 17
Fish Biomass Killed in Hypoxia Fish Kills

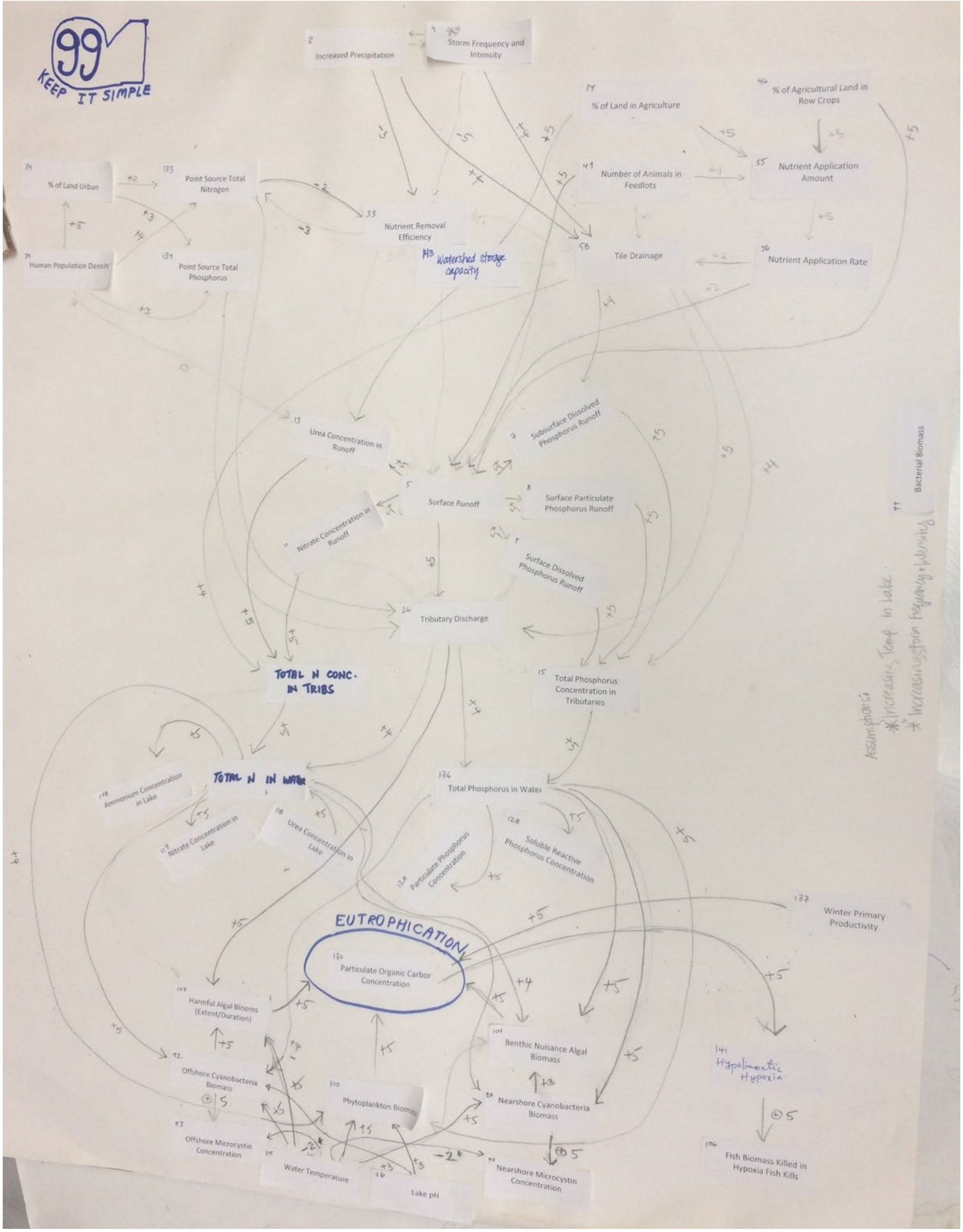
Team 2 (continued)



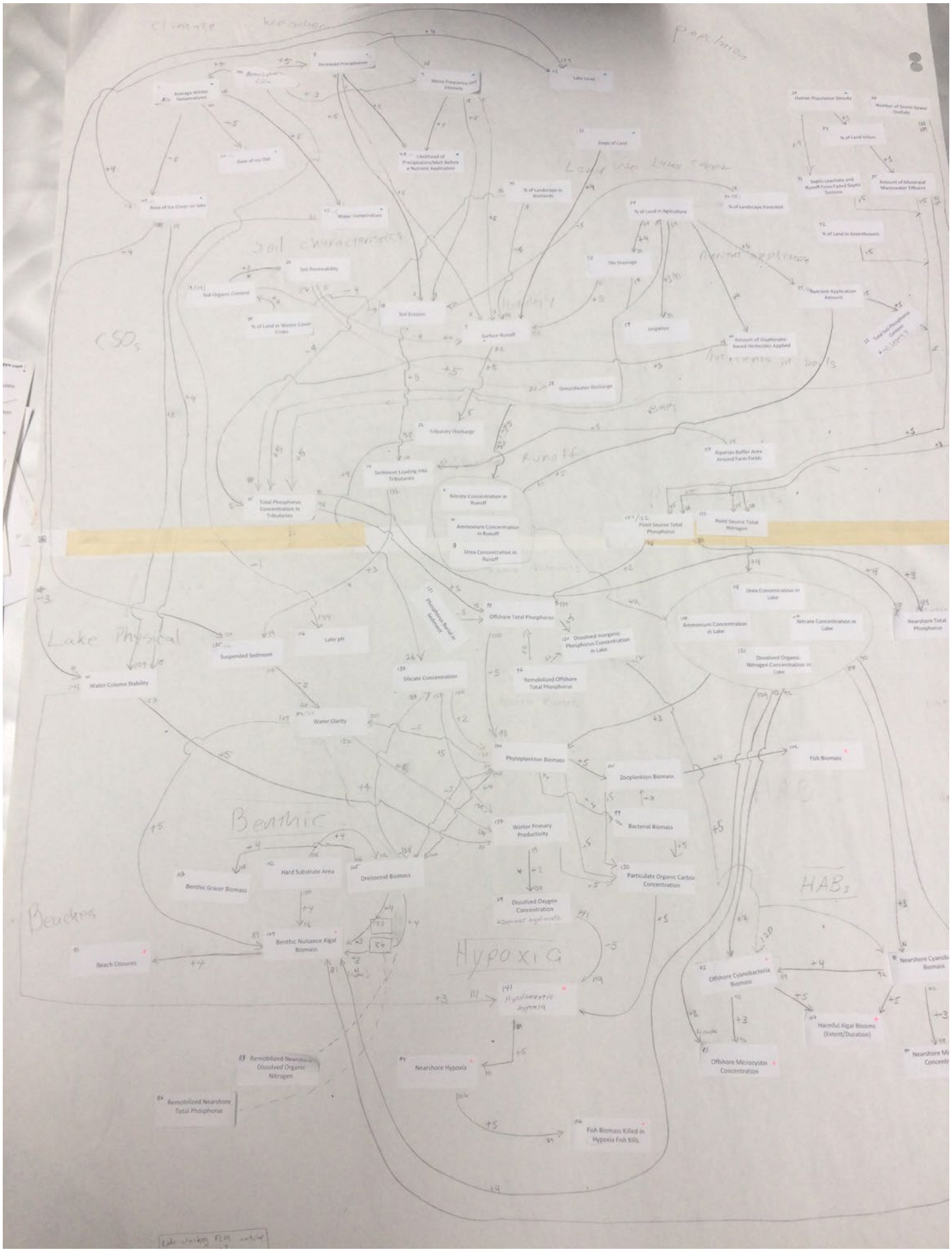
Team 2 (continued)



Team 3:


KEEP IT SIMPLE
Increased Precipitation
Storm Frequency and Intensity
% of Land in Agriculture
% of Agricultural Land in Row Crops
% of Land Urban
Point Source Total Nitrogen
Human Population Density
Point Source Total Phosphorus
Nutrient Removal Efficiency
Watershed storage capacity
Number of Animals in Feedlots
Nutrient Application Amount
Tile Drainage
Nutrient Application Rate
Urea Concentration in Runoff
Subsurface Dissolved Phosphorus Runoff
Surface Runoff
Surface Particulate Phosphorus Runoff
Nitrate Concentration in Runoff
Surface Dissolved Phosphorus Runoff
Bacterial Biomass
Tributary Discharge
TOTAL N CONC. IN TRIBS
Total Phosphorus Concentration in Tributaries
TOTAL N IN WATER
Ammonium Concentration in Lake
Nitrate Concentration in Lake
Urea Concentration in Lake
Total Phosphorus in Water
Particulate Phosphorus Concentration
Soluble Reactive Phosphorus Concentration
Winter Primary Productivity
EUTROPHICATION
Particulate Organic Carbon Concentration
Harmful Algal Blooms (Extent/Duration)
Benthic Nuisance Algal Biomass
Offshore Cyanobacteria Biomass
Phytoplankton Biomass
Nearshore Cyanobacteria Biomass
Hypolimnetic Hypoxia
Offshore Microcystin Concentration
Water Temperature
Lake pH
Nearshore Microcystin Concentration
Fish Biomass Killed in Hypoxia Fish Kills
Assumptions
* Increasing Temp in Lake
* Increasing Storm Frequency + Intensity

Team 4:


Increased Precipitation
Storm Frequency and Intensity
Lake Levels
Average Winter Temperatures
Date of Ice Out
Likelihood of Precipitation/Melt Before a Nutrient Application
Area of Ice Cover on Lake
Water Temperature
Population
Human Population Density
Number of Storm Sewer Outfalls
% of Land Urban
Slope of Land
Septic Leachate and Runoff From Failed Septic Systems
Amount of Municipal Wastewater Effluent
% of Landscape in Wetlands
% of Land in Agriculture
% of Landscape Forested
% of Land in Greenhouses
Soil characteristics
Soil Permeability
Soil Organic Content
% of Land in Winter Cover Crops
Soil Erosion
Surface Runoff
Tile Drainage
Irrigation
Nutrient Application Amount
Amount of Glyphosate-based Herbicides Applied
Nutrients in Soils
CSOs
Groundwater Recharge
Tributary Discharge
Runoff
Riparian Buffer Area Around Farm Fields
Sediment Loading Into Tributaries
Total Phosphorus Concentration in Tributaries
Nitrate Concentration in Runoff
Ammonium Concentration in Runoff
Urea Concentration in Runoff
Point Source Total Phosphorus
Point Source Total Nitrogen
Phosphorus Burial in Sediment
Offshore Total Phosphorus
Dissolved Inorganic Phosphorus Concentration in Lake
Urea Concentration in Lake
Ammonium Concentration in Lake
Nitrate Concentration in Lake
Dissolved Organic Nitrogen Concentration in Lake
Nearshore Total Phosphorus
Lake Physical
Suspended Sediment
Lake pH
Water Column Stability
Silicate Concentration
Remobilized Offshore Total Phosphorus
Water Clarity
Phytoplankton Biomass
Zooplankton Biomass
Fish Biomass
Bacterial Biomass
Winter Primary Productivity
Particulate Organic Carbon Concentration
Dissolved Oxygen Concentration
Benthic
Hard Substrate Area
Dreissenid Biomass
Benthic Grazer Biomass
Benthic Nuisance Algal Biomass
Beaches
Beach Closures
Hypoxia
HABs
Offshore Cyanobacteria Biomass
Harmful Algal Blooms (Extent/Duration)
Offshore Microcystin Concentration
Remobilized Nearshore Dissolved Organic Nitrogen
Remobilized Nearshore Total Phosphorus
Nearshore Hypoxia
Fish Biomass Killed in Hypoxia Fish Kills