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Article

Using Fuzzy Cognitive Mapping as as Planning Tool for Uurban Water Quality: A Case Study of Urban Phosphorus Flows

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Abstract: The re-emergence of algal blooms in the Great Lakes, years after the problem appeared to be solved, suggests the need for a new approach understanding and managing this issue. The previous strategy and targets in the first Great Lakes Water Quality Agreement focused on urban point source contributions, whereas the current re-emergence is now linked to non-point sources from urban areas and agriculture. Fuzzy cognitive mapping was used to describe the complexity of both contributions to Lake Erie, most recently focusing on urban point and non-point contributions. The complexity of the maps, and the strong contributions of multiple factors highlight the need, not only for multiple approaches, but across multiple pathways. The maps also indicate the large gaps in data that would be required to use precise numerical models to simulate the flow of phosphorus through urban areas

Keywords: fuzzy cognitive mapping; urban; phosphorus.

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1. Introduction

Models are often used to describe complex systems, for developing scenarios of the future, predicting the future or asking what-if questions to increase our understanding of the system. Complex systems are difficult to describe precisely because of the amount of numerical information required on each component. Even if sufficient data are available, the problem at hand might be of the wicked variety, which in addition to the complexity and the lack of data, involve many stakeholders and present no obvious or easy solutions (4) yet a decision is required (6). One such problem is the control of phosphorus loadings from urban areas into a receiving body such as a lake or a river. Phosphorus essential for life, but too much phosphorus in an aquatic system leads to nuisance and harmful algae. This has become a problem most recently in the Great Lakes with the re-emergence of Cladophora, cyanobacteria and eutrophication in Lake Erie, despite evidence that total phosphorus loadings are at or near the target levels that were deemed adequate to prevent these problems. Findings of various task groups and symposia suggest that changes in the form rather than just the quantity of phosphorus may be responsible (2).

This research focuses on understanding how phosphorus moves through urban areas from point source and non-point source contributions. In urban areas, the typical point sources are wastewater treatment plants (WWTP) and combined sewer overflow while stormwater runoff accounts for non-point sources. Previous targets in the first Great Lakes Water Quality Agreement had focused on only urban point-sources (1). To manage phosphorus flows requires an understanding how it flows through urban areas and the extent of the complexity of this system. Fuzzy cognitive mapping (FCM) is a means by which expert experience with an issue is solicited to map out complex systems that lend themselves to a network description, with specific inputs and outputs. FCM is ideal when a system is poorly understood and/or when insufficient data are not available to support more precise modelling efforts. FCM was used to map out urban phosphorus flows, the links to eutrophication and the analysis of the maps provides some new insights to managing this issue.

2. The Fuzzy Cognitive Mapping Process

FCM produces networks or maps that are based on defined nodes and causal relationships between these nodes, such that the value of a node increases or decreases. Ironically, even though the model is qualitative, the nodal variables must be countable. For example, soil type would not be acceptable as a node, whereas soil carbon content and other quantitative measures would have to be used as a proxy of soil type. The basic information in the relationship between two nodes is the direction and whether the relationship increases or decreases the value at the receiving node (6).

A simple example is the linkage between factors that lead to eutrophication (Figure 1). In this example, the factor forest land cover decreases phosphorus, but Zebra Mussels increase phosphorus and hence the outbreak of Blue-green algae and Cladophora. Note that the relationships are causal or at least directional with a sign indicating whether the value at the receiving node increases or decreases. The fuzziness is introduced by having multiple stakeholder teams describe the relationships (2) and fuzzy causal functions with real numbers in $[-1, 1]$ are applied to the connections (3). In a workshop setting, this made it possible to tap into the diversity of expertise, even incorporating disagreements in how the participants viewed the system. The participants are divided into groups, and each group produces its own map. The maps are then aggregated – there are various options available for aggregating the maps – to produce a consensus.

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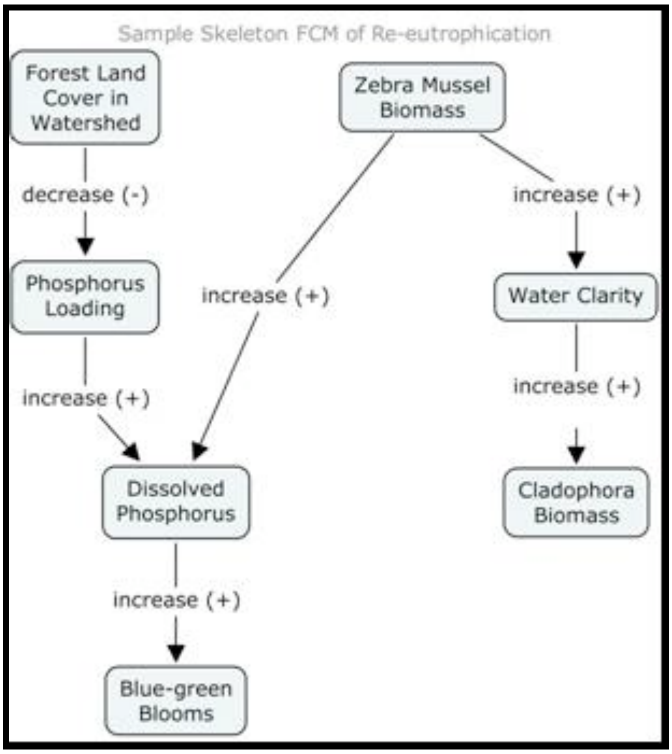
A series of fuzzy cognitive maps and an aggregate map was created by participants in an International Joint Commission (IJC)-sponsored workshop and a Lake Erie Lakewide Management

Program workshop, dealing with the re-emergence of algal blooms in the Lake Erie (2). The intent was to tap into the diversity expert opinion in order to increase our understanding of the causes of recent increases in eutrophication that seem to be appearing in the Great Lakes. One innovation to this process was the use of multiple weights (Table 1), not only indicating the strength of the relationship, but also the confidence, the spatial extent as well as the temporal extent (5). The weights can be scaled between 0 and 1 or between 1 and 5. In the analysis, the direction of the relationship will determine the sign of the weights.

Figure 1. A simplified cognitive map.



In March 2012, the first workshop was held to clarify the urban-land-eutrophication linkage, which produced four different maps. Before the workshop, participants were sent a preliminary list of 125 possible variables to include in the map. By the end of the day, this list had increased to 150, although most maps used approximately 90 – 100 variables. This list of nodes included over 25 urban management practices to reduce phosphorus flows. A similar FCM process was used previously, to define a separate map for the phosphorus loadings into Lake Erie due to agriculture, which is omitted here due to space (5).

Table 1. Weights Describing the Relationships between pairs of nodes

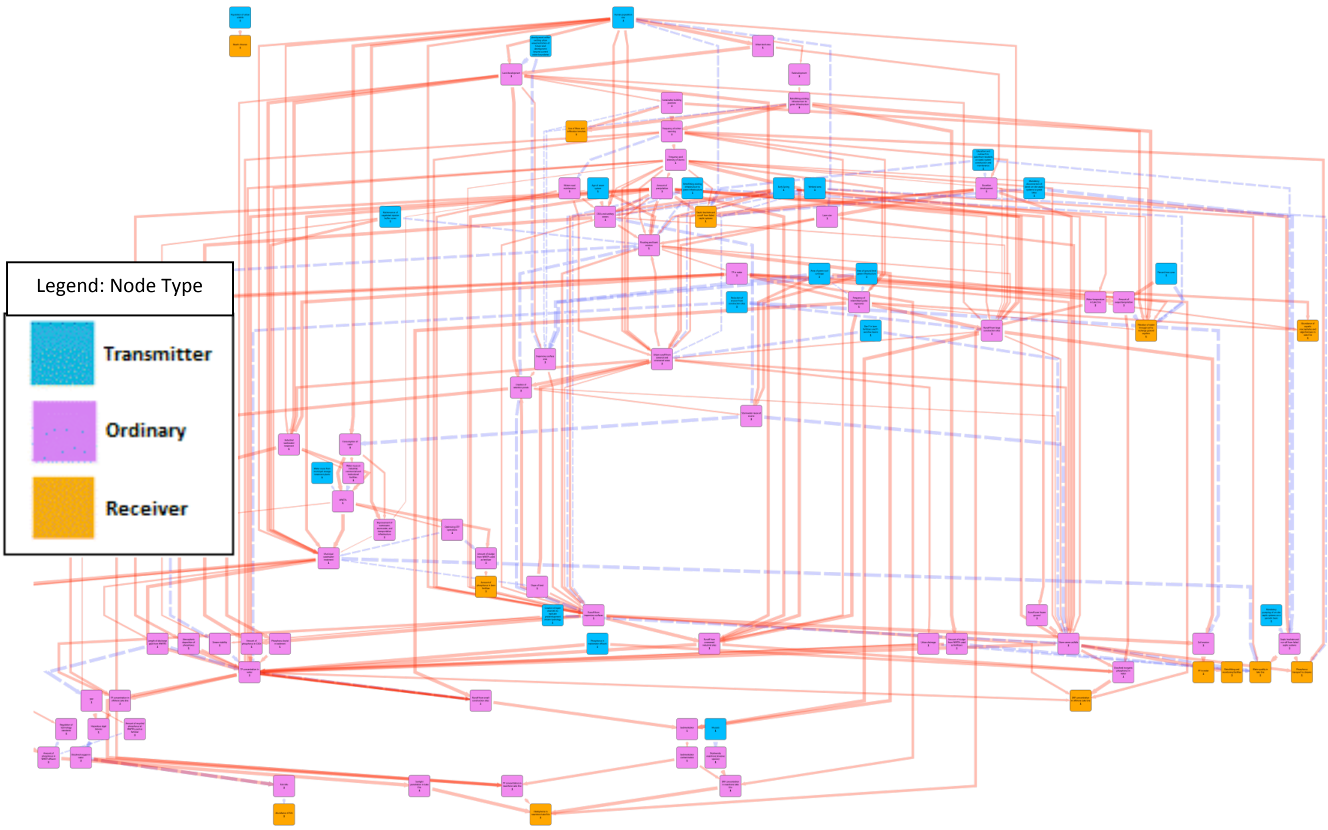
Weight	**Low Value**	**High Value**
Importance/strength	unimportant	very important
Spatial extent	local relationship	relationship holds everywhere
Temporal extent	rare occurrence	relationship always holds
Time to response	very long lag time	immediate response
Scientific certainty	basis for certainty	strong scientific agreement
Team's confidence	little confidence	very confident in scoring
Change feasibility	uncontrollable	very controllable

3. Experimental Section: Analysis of the Consensual Map

The resulting urban maps were analyzed with the customized software, Fuzzy Aggregated Linkages Within Environmental Bounds (FALWEB), which was developed for these FCM processes and the subsequent analysis. FALWEB allows for the entry, display, map aggregation and flow modelling through the network. The aggregate map is a consensus of all four maps, in this case developed using a confidence weighted mean from the weights attached to the linkages by each of the four teams.

However, although the maps are so complex that they are difficult to visualize in this document. (Figure 2), it is possible to gain some insight into the process. The red lines indicate pathways that increase phosphorus as it flows through the urban areas. The blue lines represent processes that decrease phosphorus; the darker the colour, the greater the aggregated weight. Even with more than 25 management variables that could be incorporated into the map, there are far more ways to increase than to decrease phosphorus loadings. FALWEB also divides the nodes into Transmitters, Ordinaries and Receivers. Transmitters are the drivers for the process; they only output material. Ordinaries receive and ouput material and Receivers do not output to any other nodes. In this exercise, the Receivers were nodes that dealt with the algal blooms.

Figure 2. The Consensual Aggregation of the Four Maps of Urban Phosphorus Flow Indicating Transmitters, Receivers and Ordinaries



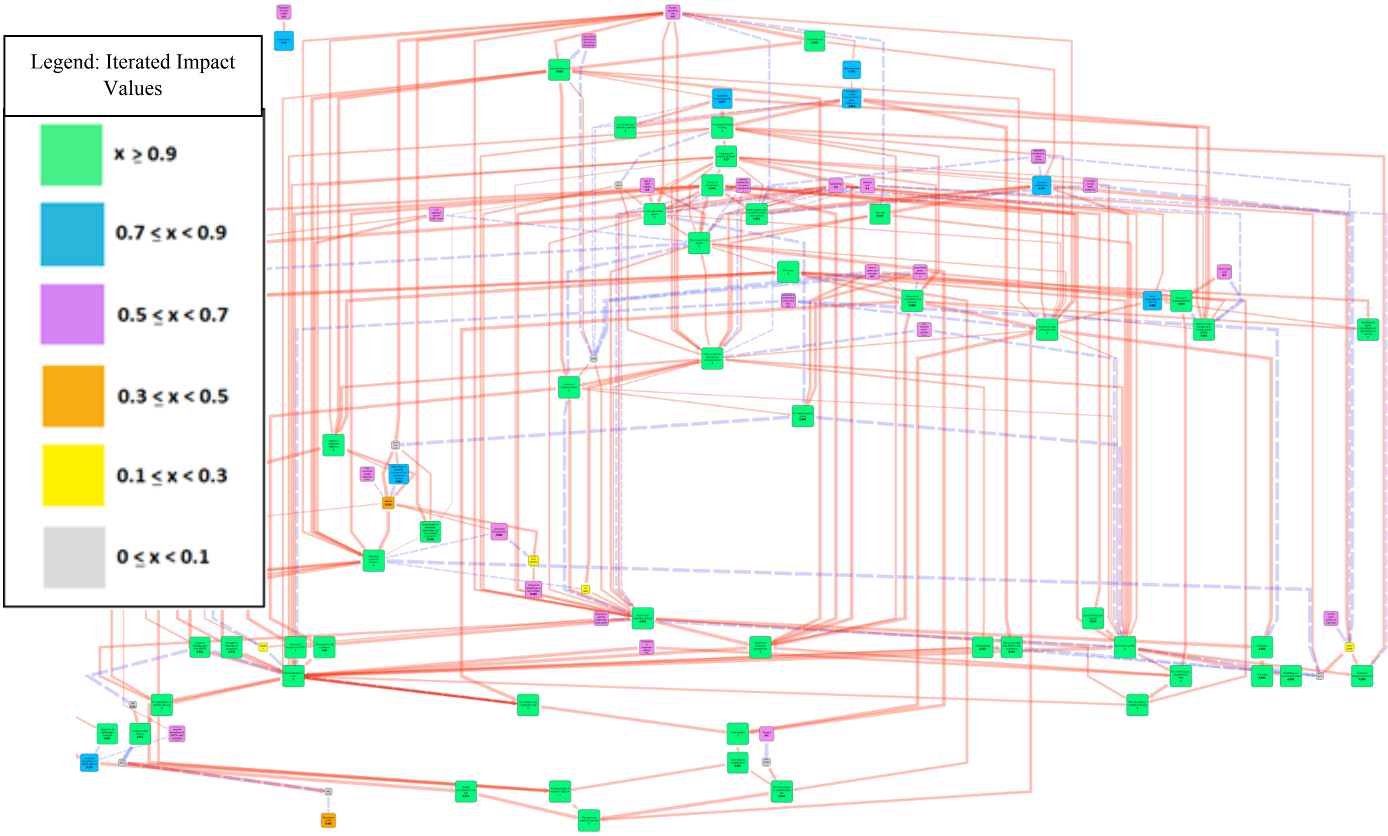
There are some key features about this map. Note the number of nodes and that most of the connections are red, meaning that phosphorus is increasing as it flows through a city. The blue lines indicate linkages that are reducing phosphorus flow and represent a number of management practices embedded into the map. Although most of the nodes are Ordinaries, there are Transmitters embedded deep into the map and Receivers embedded near the top of the map (the process begins at the top). If the management strategy is to focus on the Transmitters, this is difficult as many of them are beyond our control, such as precipitation or atmospheric deposition, but there are transmitters the transmitters that occur deep within the map would also complicate this strategy.

FALWEB's analysis uses the strength of the linkages to determine the relative contribution of each node in the network. Each node is assigned an initial weight of 1.0. Treating the map as network, FALWEB runs the network until a stable solution is reached. Those nodes that have the highest weights, are the largest contributors to the process. These are the factors to manage in controlling phosphorus. The nodes are colour-coded by weight in Figure 3, with the green colour indicating a relative weight that is greater than or equal to 0.9. In this case, most of the nodes (57) in this map fall into this category. A list of the top 45 nodes is provided in Table 2.

Table 2. The 45 highest weighted nodes and wiehgts in the stabilized Consensual Map.

Aquatic macrophytes and algal biomass (1)	Dissolved inorganic phosphorus in water (1)	Retrofitting and monitoring facilities (0.993)
Use of retention ponds (1)	SRP concentration in offshore Lake Erie (1)	Filtration of water through soil to ground aquifers (0.992)
Use of filters and infiltration trenches (1)	Runoff from small construction sites (1)	Septic leachate and runoff from failed septic systems (0.992)
TP in water (1)	Industrial wastewater treatment (1)	Phosphorus burial in sediment (0.99)
Industrial wastewater treatment (1)	Municipal wastewater treatment (1)	Land development (0.984)
Frequency of winter warming (1)	Runoff from unsewered industrial sites (1)	Amount of sludge from WWTPs used as fertilizers (0.984)
Amount of phosphorus in CSOs (1)	Sedimentation (1)	Atmospheric deposition of phosphorus (0.979)
Runoff from large construction sites (1)	Storm sewer outfalls (1)	Runoff from frozen ground (0.979)
Flooding and bank erosion (1)	Frequency of intermittent pulse exposures (0.999)	Sunlight penetration in Lake Erie (0.975)
Urban runoff from sewered and unsewered areas (1)	SRP concentration in nearshore (0.999)	Hazardous algal blooms (0.971)
CSOs and sanitary sewers (1)	Soil erosion (0.999)	Frequency and intensity of storms (0.97)
TP concentration in water (1)	Phosphorus transport to streams (0.999)	Sedimentation contamination (0.953)
TP concentration in offshore (1)	Runoff from impervious surfaces (0.995)	Urban drainage (0.953)
TP concentration in nearshore (1)	Amount of precipitation (0.995)	Retrofitting and monitoring facilities (0.993)
Cladophora in the nearshore (1)	Amount of evapotranspiration (0.993)	Filtration of water through soil to recharge ground aquifers (0.992)

Figure 3. The Consensual Aggregation of the Four Maps of Urban Phosphorus Flow by Weight (Relative Contribution to Urban Phosphorus Flow).



4. Conclusions (M_Heading1)

The reemergence of algal blooms in Great Lakes requires a different approach to managing the problems. Although the previous reductions throughout the 1970s and 1980s were achieved through urban point-source targets, the map of urban phosphorus flows suggests that the process is far more complex than envisaged in the 1970s. There are almost 50 factors, approximately 2/3 of the factors in the process, that are weighted as being of the highest importance in urban phosphorus flows. The consensual map also indicates that there are transmitters and receivers embedded throughout the process, not just at the beginning and the end. The consensual map already contains several management practices, but their impact (blue lines) is very limited both in terms of the number of connections to reduce phosphorus and the strength of those connections (as indicated by the thickness of the line). These management practices reflect the current thinking about best management practices applied to controlling urban phosphorus loadings. Any management strategy will have to be multi-nodal, intersecting many of these pathways, in order to have an impact.

FCM has been shown to be a useful technique for eliciting diverss stakeholder perspectives and combining them into one consensus. The resulting process map is a first step in developing a management strategy for phosphorus in this case, but the method is applicable to range of other issues, particularly wicked problems characterized by many contributing factors, lack of precise, numerical data and diverse opinions.

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Conflict of Interest

The author declares no conflict of interest.

References and Notes

1. International Joint Commission. (1987). *Revised Great Lakes Water Quality Agreement of 1978.* Governments of Canada and the United States.

2. International Joint Commission. (2011). *Fifteenth Biennial Report on Great Lakes Water Quality.* International Joint Commission.

3. Kosko, B. (1986) Fuzzy cognitive maps. *Int. J. Man–Machine Stud*. 1, 65–75.

4. Mason, R.O., Mitroff, I.I. (1981) *Challenging strategic planning assumptions: Theory, cases and techniques*. Wiley, New York.

5. Martin, J.P., J. Cuthbert and J.J.H. Ciborowski. 2010. Lake Erie Land and Water - Clarifying the Agriculture - Eutrophication Linkage. Summary Report 1. *Proceedings- Lake Erie Millennium Network Research Needs Workshop 4.4*, 23 March 2010, London, ON.

6. Ösezmi, U. and Ösezmi, S.I., 2004. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, 176: 43-64