Prospectus

Wavelet-based Neural Networks for Predicting and Identifying Ecological Regime Shifts

(Technical Topic)

An Actor-Network Theory Approach to Identifying Vulnerabilities in the U.S. Lake Erie Action Plan

(STS Topic)

By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

With continuing environmental deregulation and urban growth in the face of worsening climate change, our aquatic ecosystems are under immense pressure (Burke 2019; Rott 2018). Nutrient loading from non-point sources like agricultural and urban runoff have pushed environmental equilibria towards more frequent harmful algal blooms (HABs). These algal blooms produce neurotoxins and use up oxygen in the lake, spelling disaster for local wildlife and regional economies (Smith et al, 2019). In Lake Erie, for example, these blooms have shut down fisheries, discouraged tourism, made potable water more expensive, and killed off large portions of the lake ecosystem (Carmichael, 2013). If trends continue, HABs in Lake Erie could cost the surrounding communities of Ontario, Ohio, and Michigan an estimated $2.5 billion (Burford et al, 2019; Smith et al, 2019).

Existing monitoring techniques are effective for understanding and forecasting aquatic ecosystems as climate change makes their behavior more unpredictable (Burford et al, 2019). These monitoring programs are essential for government planning, community safety, wildlife welfare, and public health (Kidwell, 2015). Filtration mechanisms constructed at in Ohio farms have proven effective for reducing dissolved phosphorus, the primary nutrient responsible for algal blooms, from entering tributaries through runoff (Ohio Sea Grant, 2018).

However, these technical solutions alone are not enough to protect and monitor the health of aquatic ecosystems. Methods for addressing HABs and applying technical solutions are severely underfunded and often lack the support of those involved (Schmitz, 2019; Erbentraut 2017). One must consider both the social and technical components of combating HABs and protecting aquatic ecosystems to ensure they work constructively with each other. Without an effective sociotechnical approach, technical solutions could prove ineffective, and the yearly projected costs of HABs could double (Smith et al, 2019).

To explore the sociotechnical nature of this problem, I will investigate the Lake Erie Action Plan, which aims to reduce phosphorus loading into Lake Erie by 40% and improve research and monitoring of the lake ecosystem. By analyzing how this plan is vulnerable to failure, I can better understand the obstacles our technology would face to effective implementation.

Below, I outline a novel technical approach for monitoring and forecasting the conditions of aquatic ecosystems using modern statistical methods. I also apply actor-network theory to untangle where governments are succeeding and failing to mobilize human and non-human actors to reduce phosphorus loading into the West Lake Erie Basin.

Technical Problem

Monitoring and forecasting the health of our lakes grows more important as global temperatures rise, local ecologies becomes more unpredictable, and environmental water protections are relaxed (Stafford et al, 2013). The ecology of these aquatic ecosystems is heavily dependent on the composition and volume of nutrients flowing into and out of them. With an overloading of nutrients, particularly phosphorus and nitrogen compounds, the state of an ecosystem can become unstable. The structure of the food web, balance of nutrients, and population of each species can shift rapidly in what is called a regime shift, a transition from one ecological equilibrium to another. One such transition in lake ecosystems is from an oligotrophic state with low-biomass to a eutrophic state with high plant and phytoplankton biomass (Carpenter, 2003). This transition is what occurs in cyanobacterial algal blooms that produce toxins and endanger humans, animals, and the long-term health of the ecosystem (Kidwell, 2015). The ability to predict if and when these regime shifts will occur would prove a useful tool for mitigating harmful ecological transitions like these (Ontario Ministry of the Environment and Climate Change, 2017).

While they occur on the relatively short timescale of a few months, regime shifts in lake ecosystems are accompanied by pretransition indicators that can act like early-warning systems in ecological timeseries (Carpenter et al, 2011). There are three theoretical features that indicate an increased likelihood of transition: critical slowing down, flickering, and frequency multimodality. In the first of these, the system equilibrates from a perturbation more slowly because an underlying instability in the ecosystem. Existing techniques use an increase in temporal autocorrelation to measure this feature. Next, in flickering, an ecosystem transiently “flips” into another regime because of stochastic fluctuations or patchiness This is marked by an increase in both autocorrelation and signal variance. Lastly, frequency multimodality is found when characteristic oscillations of other regimes begin forming underneath the current regime (Scheffer et al, 2012). This requires spectral analysis. Autocorrelative methods to detect trends in multimodality have tended to produce false positives, weakening their predictive power (Andersen et al, 2008; Hsieh, 2007).

These early warning features and their corresponding metrics are insufficient to provide a comprehensive understanding of an ecological regime and its stability. There is currently no single metric that reliably evaluates the presence of all three pretransition characteristics. Additionally, measures like autocorrelation and variance are calculated in a fixed-length moving window across the timeseries; they cannot measure across the diverse timescales characteristic to aquatic ecology (Cazelles et al, 2008).

There is a deficiency of statistical methods for forecasting aquatic ecosystems while climate change, anthropogenic over-enrichment, and hydrological modifications threaten the health and stability of our lakes and waterways (Burford et al, 2019). Aquatic ecosystems that are most threatened are also those that provide the most economic and social benefit. Harmful regime shifts like algal blooms can kill local aquatic life, endanger the health of residents and tourists, and cost millions to the economy (Wilson et al, 2018). Controlled experiments by Pace et al (2017) have shown that these harmful algal blooms can be prevented if early-warning signs are detected and acted on. This remains impossible if we cannot predict real-world regime shifts.

The goal of this project is to design and test a method for identifying and predicting regime shifts in aquatic ecosystems. This method will be built on discrete wavelet transforms and both convolutional and recurrent neural networks. Wavelet analysis convolves time series with a parent function stretched over multiple timescales, and characterizes the autocorrelation, variance, and multimodality of a timeseries in a transformed dataset (Rouyer et al, 2008). Incorporating wavelet analysis allows for non-stationary timeseries to be analyzed while maintaining evaluation at large timescales (Torrence & Compo, 1998). Generally, the neural networks will act to classify features in the wavelet-transformed dataset and identify where regime shifts are likely. Convolutional neural networks will be used to further convolve the wavelet transformation of a stationary timeseries and classify if a time series is present. This stage of the project will focus on feature identification and classification (Fujieda et al, 2018). A recurrent neural network will be used on iterative wavelet transformations of non-stationary timeseries, with the end goal of forecasting probable regime shifts (Petneházi, 2019).

Our novel approach has potential. Because the indicators regime shifts are encoded in the wavelet transform data, the neural networks are only fed the most important information to make classifications and predictions. Additionally, neural networks can distinguish non-theoretical features of ecological regime shifts that may be present in an applied setting. They can then harness these new features to drive predictions.

I will develop a software package in R capable of the previously described analysis. Neural networks will be trained on both simulated and empirical data of phytoplankton-nutrient interactions. The end goal will be verification of our prediction methodology on empirical data.

STS Problem

The West Lake Erie Basin provides its neighbors of Ohio, Ontario, and Michigan with fresh water, tourism, fishing, and economic growth, but this is all threatened by harmful cyanobacterial algal blooms. These cyano-HABs had been largely eliminated from the West Lake Erie basin in the mid-1980s, thanks to an 80% reduction in nutrient inputs from wastewater flows and other point-sources. As a result, the local economies of neighboring Ohio, Michigan, and Ontario flourished with tourism, coastal development, and agriculture. Since the turn of the century, however, cyanobacterial biomass in Lake Erie has been rising, and harmful algal blooms (HABs) have become more frequent (Wilson et al, 2018). Increased nutrient loading from growing cities and farmlands is likely the cause (Wilson, 2018).

With climate change threatening to worsen the situation, policymakers, advocates, and stakeholders are taking action to protect the future of Lake Erie (Michigan.gov, 2019; Burford et al, 2019). U.S. and Canadian governments, national and local, have attempted to bring together relevant stakeholders together to find long-term solutions. They aim to reduce phosphorus loading into the West Lake Erie Basin and by 40% and have targeted agricultural runoff as the primary source.

In the past few years, the United States' Lake Erie Action Plan has struggled to make progress towards the international goal despite being the worst offender in phosphorus loading. As the federal government reduces funding for Lake Erie programs and loosens environmental water protections, advocates have pointed to federal subsidies as key to improve our approach (Burke, 2019; Schmitz, 2019; Ermentrout, 2017). However, complications with the Lake Erie Action Plan extend well beyond federal funding and support. Farmers in the Lake Erie watershed do not share the vision of the Lake Erie Action Plan. They are not supportive of the drastic measures needed to address the threat of HABs, and have empowered their representatives to obstruct such measures. (Chow, 2018; Hancock 2018).

A holistic solution to protecting Lake Erie's future needs to address why stakeholders, particularly farmers, are opposed to the current approach to solving HABs in Lake Erie. By investigating how this network of communities, governments, technologies, and environments is susceptible to failure, we can better understand how interconnected sociopolitical factors can hinder the effectiveness of technological solutions.

I will apply actor network theory, which analyzes the relationships between human and non-human actors as they operate within a network designed with a specific goal (Cressman, 2009; Rivera, n.d.). By framing each stakeholder and resource as an agent in relation to all the others, we can untangle the complicated obstacles facing the U.S. Lake Erie Action Plan. With the United States federal government as the network builder, it is responsible for recruiting all relevant parties into its Lake Erie Action Plan. Analyzing interessement, where actors find justification for enrolling into the network, will be particularly useful for understanding how this network is vulnerable to political opposition (Rott, 2018).

Conclusion

To accomplish the goal of an integrated sociotechnical project, I will both develop novel statistical techniques for forecasting aquatic ecosystems and clarify the sociopolitical obstacles facing the Lake Erie Action Plan using actor-network theory.

Our technical project will create a more robust method for monitoring the condition of aquatic ecosystems that incorporates modern statistical approaches and analysis long-term trends. This tool can aid organizations in mitigating the economic, public health, and environmental consequences of HABs. Simultaneously, it can provide researchers with a tool for understanding the characteristics regime shifts like HABs and aid in the discovery of new solutions for mitigation.

Our sociopolitical analysis will provide a path forward for policymakers and advocates towards reducing the frequency of HABs in the long term. Focusing on state and federal governments as network builders, I will be able to investigate resistance to action on Lake Erie and understand how networks like it are vulnerable to failure.

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