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Spatio-Temporal Control of Nutrient Pollution from Organic Waste

Yicheng Hu[a], Gerardo Ruiz-Mercado[b] and Victor Zavala[a*]

[a]*Department of Chemical and Biological Engineering, University of Wisconsin-Madison, 1415 Engineering Drive, Madison 53706, USA*
[b]*National Risk Management Research Laboratory, U.S. Environmental Protection Agency, 26 W. Martin Luther King Drive, Cincinnati 45268, USA*
victor.zavala@wisc.edu

Abstract

Better management of anthropogenic organic waste and other primary sources of nutrient pollution such as agricultural, municipal, and industrial waste, will reduce the human impact on the environment. Harmful algal blooms (HABs) are a major environmental impact from organic waste and nutrient pollution. HABs can pose severe threats to human health due to the release of dangerous toxins in fresh or marine water that can negatively affect public health, increase treatment costs for drinking water, and cause enormous economic loss in industries that depend on clean water. In this study, the effect of decisions made in the organic waste supply chain (SC) on reducing the potential for HABs is investigated by integrating three types of models: a SC optimization model, a nutrient transport model, and an algae growth model. This contribution presents a comprehensive spatio-temporal management strategy for short-term HAB reduction by adjusting components in the SC, including technologies, logistics, nutrient management plans (NMPs) or environmental costs, and seasonal waste storage planning. In addition, it is presented a case study of the Upper Yahara Watershed in the State of Wisconsin to illustrate the practicability of this modeling framework.

Keywords: supply chain, nutrient pollution, spatial-temporal control, harmful algal blooms

1. Introduction

The role of nutrient pollution (specifically nitrogen and phosphorous) is central to the underlying causes of HABs. Sources of nutrient pollution are classified as either non-point source or point source. Non-point sources include agricultural land, stormwater etc., and the point sources include permitted facilities, e.g. wastewater treatment plants (WWTPs). Complex point and non-point nutrient management strategies will be required to achieve a more comprehensive and permanent solution to controlling the nutrient pollutions. The increasing rate of HAB development is a complicated problem faced by human populations around the world. Algal species involved in a HAB can generate significant levels of toxins threatening public health. According to Heisler et al. (2008), HABs have economic impacts in the form of remediation costs for water treatment and reduction in property value of the impacted areas . Graham et al. (2009) estimated that 30% of lakes from 36 states in the US have reported toxic cyanobacterial bloom issues . The US Environmental Protection Agency (US EPA) reported the tourism losses of one billion dollars annually and commercial fishing losses on the order of tens of millions of dollars annually [1].

By designing an appropriate transportation network for organic matter and incorporating technology placement for treatment and processing, the nutrients in organic waste can be more efficiently recycled for agricultural use in the growth of crops, feeding of grazing animals, and ultimately for human benefit. However, from Zandi Atashbar et al. (2018), current sustainable SC design studies typically incorporate metrics such as global warming potential and eutrophication potential which measure the chronic environmental impacts. Yet, the effects of seasonal variations in nutrient loading must be considered. Therefore, an extended modeling framework is needed to better describe the explicit environmental consequences caused by decisions made in the organic waste SC design.

In this work, we apply, adapt, and combine multiple types of modeling tools, including a SC design model, a nutrient transport model, and an algae growth model to create an optimization framework that analyzes the effect of nutrient controlling strategies in SCs on HABs. We present a case study in the Upper Yahara Watershed in the State of Wisconsin.

2. Modeling Framework

In this section, we introduce a modeling framework to connect the decision-making and control strategies in the SC with the environmental consequence of HABs. The modeling structure is shown in Figure 1.

Algae growth shows seasonal dependence, and this is because its growth is affected by water temperature, sunlight, nutrient concentration, and other factors. Steady-state modeling will not adequately capture the impact of seasonality, nor will models with large time steps (e.g. annual based decision making). For example, nutrient leaching in cold months will raise the probability of HABs in the spring. Therefore, management and prevention actions must be taken in advance, but there is still ambiguity about the optimal lead time for actions to be effective. The models for algae growth, nutrient transport, and SC, all have an explicit time dependence.

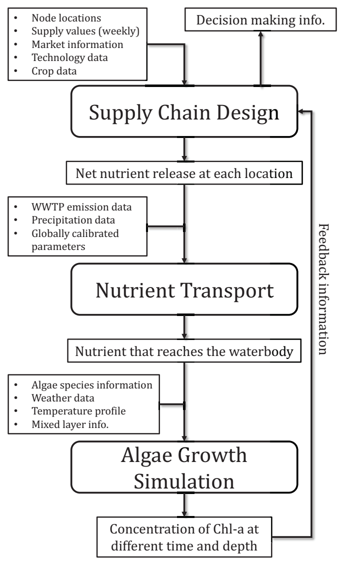

Figure 1: Modeling structure

2.1. Supply Chain Model

We extend the supply chain framework from Sampat et al. (2017) and Hu et al. (2018). The SC model is a constrained dynamic optimization model, which takes the input of node locations (e.g., dairy farms), the weekly supply amount of organic waste, market information including demand amount and price for each product, technology data (yield factors, investment and operational costs), and crop data, such as the crop type, yield, growing season, and nutrient uptake rate.

[1] https://www.epa.gov/nutrientpollution/effects-economy

The SC structure is shown in Figure 2. The farms can send organic waste to transportation sites to process it, storage systems to store it temporarily, or directly apply it to agriculture lands. The value-added products from technologies can be purchased by external customers. The main decision variables in the model are transportation flows, inventory levels, installation of technologies and storage systems, and amount of commercial fertilizers applied. The SC model can also output the amount of applied organic waste, which can be fed into the nutrient transport model to support runoff calculation.

The constraints in the optimization model include: the flow conservation at each node (product balance), the product conversion at technology sites, capacity constraints for demand, inventory, and processed waste, the nutrient requirement for each crop at each node and time period, and the economic metrics. The objective function is to minimize the overall costs plus the excess nutrients in the system, where the weight can be interpreted as unit environmental costs or the strictness of environmental policies regarding nutrient management plan at each node.

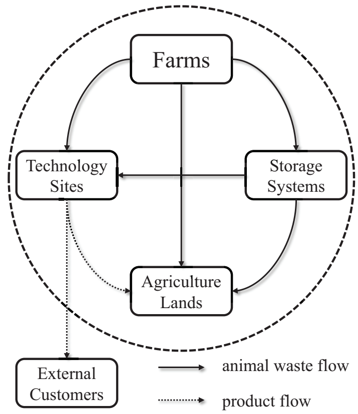

Figure 2: Supply chain structure

2.2. Nutrient Transport Model

A nutrient transport model tracks the nutrient transport process from point and non-point sources to surface water. To reduce the computational burden, increase the compatibility of the framework, and generate results at preliminary development stages, instead of using advanced and data-intensive simulation tools such as SWAT (Neitsch et al. (2011)), we select a watershed-level model called NEWS2 (Nutrient Export from WaterSheds 2) proposed by Mayorga et al. (2010). The NEWS2 model is a more general model that takes input data of WWTP emission data, precipitation data at a watershed level, globally calibrated parameters, and the net nutrient release information from the organic waste SC management model.

The model calculates the phosphorus and nitrogen that reach the water body considering both the contributions from point and non-point sources. The point source part is calculated using the population data and nominal nutrient release per person. The contribution from non-point sources is calculated using some global parameters, precipitation data (which is used for surface runoff calculation), and the net nutrient release accounting for fertilizer, animal waste application, fixation and deposition, and crop need.

We note that in the application of the NEWS2 model, two main assumptions are made. First, the NEWS2 model is originally used for annual nutrient transport. We assume a biweekly nutrient transport amount can be assessed using the same approach with finer input data, and with a transport delay included. Second, we assume the model can be fit into the use of small watershed. The modeling framework is equipped with more powerful functions under these functions, which might lead to lower accuracy. We will continue to extend the scope in the nutrient transport modeling and simulation.

2.3. Algae Growth Model

An algae growth model is used to relate the nutrient concentration in a water body with the HAB level and the corresponding consequences. The algae growth model used in this framework is the PROTECH (Phytoplankton RespOnses To Environmental CHange) model, which is proposed by Reynolds et al. (2001), and takes the input of nutrient concentration data, algae species information, weather data, lake profile (e.g. temperature). The model uses the concentration of chlorophyll-a (chl-a) as a measurement of the abundance of algae.

The PROTECH model calculates the daily concentration of chl-a by considering the growth rate, the rate of decrease due to animal grazing, settling out (algae movement), and dilution. For each term, the rate is mainly related to temperature, nutrient level, and sunlight intensity. The model can output the concentration of chl-a at different times and at different depths of the lake.

3. Case Study

We apply this modeling framework to a case study considering the region of Upper Yahara Watershed within Dane County in the State of Wisconsin. This region has suffered from nutrient pollution for years. The NBI (nutrient balance index, defined as the ratio of nutrient applied to land over the amount of nutrient that is removed by crops) was 1.95 and 1.35 in the year of 2012 and 2013 respectively (Larson et al. (2016)) . For the year 2017, the NBI index was 1.46 based on our estimation. The Lake Mendota has been categorized as eutrophic since the 1980s.

In the case study, we use the crop and weather data of the year 2017. The time period of interest is from April 1st to October 31st, where the HABs are more likely to happen. The data of nutrient recovery technologies are from previous studies (Sharara et al. (2018); Sampat et al. (2018)). The decision-making procedure in this case study is illustrated in Figure 3, and the control techniques in the SC are the strictness of NMPs, the availability of nutrient recovery technologies, and the seasonal storage planning. Although the SC framework has the capability of placing facilities, the facility sites in this case study are predetermined using real data. After solving the SC optimization problem, it can provide a spatio-temporal strategy containing different transportation flows and inventory levels in different times, which is able to control the net nutrient release in the system while balancing the economic objective. Based on this procedure, we start from the worst scenario (no technologies or NMPs, and poor storage planning), and compare the effectiveness of each technique individually. Finally, we study the overall influence of adopting three techniques simultaneously. We obtain economic information from the SC model. From the difference of scenarios, we

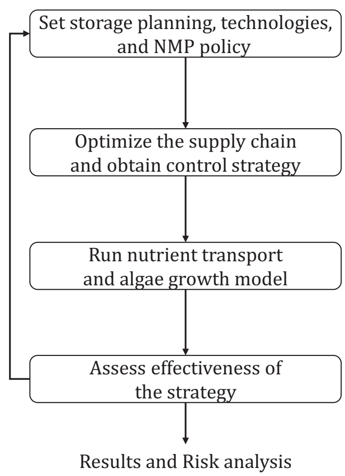

Figure 3: Decision-making scheme

can estimate the preventive cost for reducing HABs risk.

4. Results and Discussion

First, we compare the predicted TSI (trophic state index, proposed by Carlson (1977)) of the scenario closest to reality with observed data. A lake is defined as eutrophic when TSI is between 50-70. The predicted TSI is between 55 and 65; while the observed TSI fluctuates between 50 and 60, which indicates the practicability of the framework.

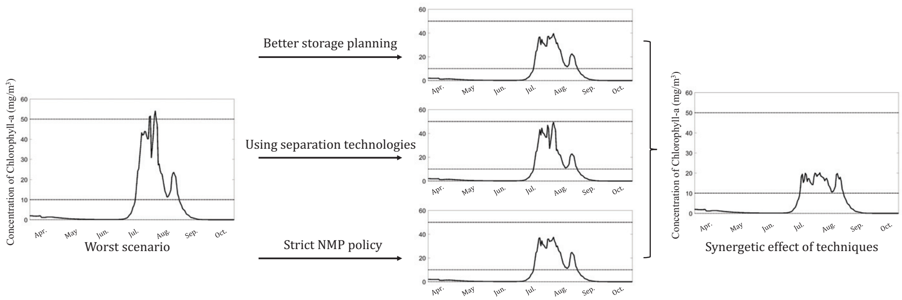

Figure 4: Model prediction

In Figure 4, we show the predicted concentration of chl-a under different control strategies. We observe that, in the worst scenario, the concentration exceeds the warning line of a high risk of acute health effect for humans suggested by the World Health Organization World Health Organization (2003) (50 mg chl-a/m^3), while the control techniques can reduce the HAB level under the warning line. From the comparison between the three control techniques, we find the incorporation of separation technologies is the less effective strategy, which may have attributed to the fact that the derived products are not valuable, and the economic driving force is not large enough. On the other hand, direct environmental policy changes (better storage planning or strict NMP policy) are more effective at controlling the nutrient runoff and thus the HAB level. Additionally, we observe that, by combining the three techniques, the HAB level can be reduced substantially, which means the strategies have an overall synergistic effect. However, even for the best scenario, the concentration of chl-a still exceeds the middle warning line (moderate risk of having acute health problems, 10 mg chl-a/m^3). This indicates that long-term effort (perennial SC optimization and nutrient management) is necessary to further eliminate the HABs risk.

From the economic results of the SC optimization problem, we can obtain the overall cost in the system (operational cost of technology, transportation cost, and fertilizer cost). For the worst scenario, the overall cost is 1.18 million USD while for the best scenario, the overall cost is increased by 32.2 % and reaches 1.56 million USD. This indicates the cost corresponding to the prevention of HABs in the same year can reach 0.38 million USD. We note that this estimation is conservative because the cost of implementing strict policies, the increased holding cost in inventory management, and the investment cost of technologies are not included.

5. Conclusions

In this work, we formulate a dynamic modeling framework by combining a SC optimization model, a nutrient transport model, and an algae growth model. The management elements in the SC network can be regarded as controlling techniques, and the output from the algae growth model can provide feedback information for the SC design. We provide a case study of Upper Yahara Watershed to illustrate the practicability of the model. We find by designing appropriate SCs, the nutrient loading in runoff can be decreased and the risk of HABs will be lower, but a corresponding cost of prevention will be incurred. In future work, we will conduct more scenario analyses and study the influence of logistics and the cost distribution at different times. We will extend our framework so that a perennial influence can be forecast.

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