Final Report for LEPF Project #SG 431-2012

Project title: Linking Land Use and Yellow Perch Recruitment

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Abstract

The effects of increasing urbanization and Global Climate Change are not limited to the terrestrial environment. Alterations in sediment and nutrient transport from a watershed can result in substantial reductions in water clarity through sediment plumes and algal blooms. These plumes and blooms have the potential to alter the growth, and ultimately the recruitment, of visually foraging fish species, such as the yellow perch (*Perca flavescens*). In this study we use Soil and Water Assessment Tools (SWAT) and Individual Based Models (IBMs) to link changes in land use and climate in the Maumee River watershed to growth of age-0 yellow perch in the Maumee Bay. Land use models show that increasing urbanization can lead to a significant reduction in yellow perch growth by altering the timing and intensity of sediment plumes. However, this effect is only seen at very high levels of urbanization, likely due to the influence of non-point source agricultural runoff in the Maumee basin. Global Climate Change has the potential to reduce age-0 yellow perch growth, primarily through increased water temperatures allowing for an earlier onset, and longer duration of algal blooms in the Maumee Bay. Our results show that alterations to land use and climate in a watershed have the potential to significantly alter the growth of a visually foraging fish species by altering the timing and intensity of downstream sediment plumes and algal blooms.

Activities, timelines and workproducts:

This project will result in a chapter of N. Manning's Ph.D. dissertation, to be defended during the spring semester, 2013. Results of this research were presented by N. Manning at the 2013 Ohio State Univ. Aquatic Ecology Laboratories Research Review Conference in Columbus, Ohio, January 2013. Additionally, a manuscript is currently being prepared based on this research.

No major alterations were made to our timeline and all proposed work has been completed.

Main activities and outcomes; technical results:

The technical results of this project follow in the form of a draft manuscript, which is currently being prepared for inclusion in N. Manning's Ph.D. dissertation and for submission to a peer reviewed journal.

Changes in project, hurdles experienced, lessons learned:

Only minor changes in our experimental design were needed, and none that resulted in a substantial change from the proposed project. Primary changes included use of field measurements of sediment and algal turbidity, instead of satellite imagery to estimate the starting dates of algal blooms in the Maumee Bay. The experiment described in the technical section of this report reflect the changes, most of which were undertaken on the advice of the research committee of N. Manning,

The results of this project indicate that changes in a terrestrial environment can influence fish growth by altering the visual environment through sediment plume and algal bloom dynamics. These results are important as they highlight the interconnectedness of terrestrial and aquatic systems, and reaffirm the importance of the visual environment encountered by fish. The results of this project help to better define how human activities in a watershed can influence the aquatic life in the associated water bodies.

TECHNICAL REPORT

INTRODUCTION

The importance of understanding how our actions influence changes to our environment is becoming more pronounced in the face of expanding urbanization and global climate change (GCC). Virtually all of the ecosystems on Earth are now directly impacted by human influence (Vitousek et al. 1997), and the rate of environmental change is increasing rapidly. This is especially true for ecosystems that exist at the interface of terrestrial and aquatic systems. More than half of the world's population lives and works within a coastal watershed, and in developing nations, such as China, that number is expected to increase rapidly in the decades to come. In the United States, the population of coastal regions is growing three times faster than interior regions, and at the current growth rate, will reach 127 persons /km^2 by 2015 (Faulkner 2004).

The worlds expanding coastal populations are becoming more concentrated in large cities, with at least 14 megacities (pop>10 million), and 40% of cities with a population between one and ten million located in coastal zones worldwide (Tibbets 2002). These large cities generally have a larger "ecological footprint", or amount of resources needed to support them, than more sparsely populated rural regions. One consequence of meeting the demands for food and housing from these expanding coastal populations will be increasing agricultural and urban development in the watersheds. This extensive alteration of land use in a watershed leads to the reduction and elimination of ecologically important habitats, like wetlands and riparian zones, which act as a buffer between the terrestrial and aquatic systems. Additionally, increasing global temperatures and alterations to precipitation regimes due to GCC can further alter the terrestrial environment by modifying plant and animal community structures, and increasing a reliance on irrigation.

The effects of human expansion in a watershed are not limited to the terrestrial environment. Degradation of the terrestrial habitat in a watershed leads to the loss of both form and function of the downstream aquatic habitat. Terrestrial processes have been shown to affect virtually every aspect of water quality in their associated aquatic systems, including nutrient availability, and water clarity. Algal blooms, which are affected by nutrient availability and temperature (Anderson et al. 2002; Paerl and Huisman 2008) are, in many places, increasing in intensity and duration (Hallegraeff 1993; Sneller et al. 2003), and have become the focus of considerable concern (Dyble et al. 2003; Bridgeman and Penamon 2010; Bridgeman et al. 2012). Additionally, increasing flashiness of tributaries due to climatic and land-use changes may lead to an alteration of the timing of sediment plumes (Pfister et al 2004), producing turbid conditions during periods that have, historically, been periods of high water clarity (Sutherland et al. 2002).

Changes in water clarity due to high levels of organic and/or inorganic particles can alter the feeding ability of visual predators through light attenuation and degradation in the apparent contrast between a prey item and its background (De Robertis et al 2003). These changes in foraging rates associated with water clarity alterations are of particular interest, as they affect not only the growth of visually foraging species, but potentially the recruitment success of a population. Even small variations in age-0 growth can result in large differences in the subsequent recruitment of a population (Miller et al. 1988; Leggett and DeBlois 1994; Bergenius et al. 2002) as recruitment often hinges on growth and survival of the age-0 year class (Ware 1975; Crowder et al 1987; Post and Evans 1989; Rice et al. 1993; Cowan et al. 1996; Sogard

1997). In a series of laboratory experiments with larval and juvenile yellow perch (*Perca flavescens*), Wellington et al. (2010) found that sediment and algal turbidity differentially affected foraging in larval and juvenile yellow perch. Specifically, high sediment turbidity did not reduce the foraging rate of larval yellow perch, but did reduce the foraging of juveniles (Wellington et al 2010). Alternatively, algal driven turbidity (at all intensity levels) reduced the foraging ability of both larvae and juveniles (Wellington et al. 2010). These studies suggest that terrestrial impacts on water clarity can exert a distinct influence on the growth, and potentially the recruitment success, of larval and juvenile yellow perch.

The goal of this research is to link anthropogenic alterations in the agriculturally dominated Maumee River watershed to potential changes in the growth of age-0 yellow perch in the Maumee Bay, Lake Erie. To accomplish this goal we used the Soil and Water Assessment Tools 2005 (SWAT) to model the potential changes in the sediment and phosphorus inputs from the Maumee River watershed due to both increasing urbanization and Global Climate Change (GCC) scenarios. We then link those terrestrial impacts to alterations in sediment plume and algal bloom cycles, and ultimately, yellow perch growth in the Maumee Bay using Individual Based Models (IBM). In doing so, we address two main questions: 1) What level of urbanization is needed to see a significant change in predicted yellow perch growth in a predominately agricultural watershed, and 2) What are the potential impacts on yellow perch growth due to changes in the watershed based on predicted GCC alterations?

METHODS

Study Area

The Maumee River forms at the confluence of the St. Mary and St. Joseph Rivers, near Ft. Wayne, Indiana. The River flows northeast for approximately 120 miles to Toledo, Ohio, where it empties into the western Basin of Lake Erie through Maumee Bay (Fig. 1). The Maumee River drains the largest watershed in the Great Lakes Basin (ca. 17,000 Km^2) including portions of Northwestern Ohio, Southern Michigan and Northeastern Indiana. Land usage in the watershed is dominated by traditional row crop agriculture, which covers more than 75% of its area, with a further 15% being classified as urban/ suburban. This intensive agricultural use has contributed to the Maumee River having the highest suspended sediment discharge rate of any Great Lakes tributary. While the Maumee river contributes less than 25% of the total water that flows into the western basin of Lake Erie, it contributes more than half of the suspended sediments input, and a significant portion of the total phosphorus. This disproportionately large contribution to sediment and phosphorus along with contamination from a long history of industrial usage, particularly in the Toledo area, have led to portions of the river being listed as an Area of Concern (AOC) under the US- Canada Great Lakes Water Quality Agreement (US Army Corps of Engineers, 2009).

While the Maumee River's contribution to sediment and nutrients undoubtedly has a significant impact on the entire western basin of Lake Erie, its influence on the Maumee Bay is likely magnified. The Maumee Bay is a semicircular bay at the southwestern end of Lake Erie between 41°41'N and 41°45'N latitude, and 83°20'W and 83°29'W Longitude. The bay is defined from the main body of Lake Erie by two spits, Woodtick Peninsula to the north, and Cedar Point to the East. Maumee Bay has a surface area of approximately 48 km^2, which comprises approximately 5% of the surface area of the western basin of Lake Erie, and is uniformly shallow, with an average depth of only 1.7m. The bay is bisected by a 60 m wide, 10 m deep shipping channel that runs from the mouth of the Maumee River, 20 miles northeast into the western basin of Lake Erie. The Maumee River is Maumee Bay's largest source of water, sediment and nutrients, but the bay also receives input from the Ottawa River to the north, as well as several other, smaller creeks and streams to the east. However, the influence of these other inputs is relatively minor compared to the Maumee River, as these other inputs only account for about 2% of the flow input, and less than 1% of the sediment input into the bay. Because of the bay's shallow depth it has a relatively short water retention time, of only 5 days, as compared to 53 days for the entire western basin, and 1007 days for Lake Erie as a whole, and so water clarity conditions in the bay are often reflective of the outflow of the Maumee River.

Initial model implementation, calibration and corroboration

To achieve our goal of linking anthropogenic alterations in the agriculturally dominated Maumee River watershed to potential changes in the growth of age-0 yellow perch in the Maumee Bay, Lake Erie several models needed to be developed and linked. The steps to achieve this linkage, include: 1) development of a Soil and Water Assessment Tools (SWAT) model that accurately predicts the amount of water, sediment and nutrients leaving the Maumee River watershed, 2) conversion of the SWAT output from a daily output to a volumetric value to reflect the amount of water, sediment and nutrients in the Maumee Bay, 3) development of an individual-based model (IBM) that links sediment type and amount to the growth and abundance of young-of-the-year yellow perch, which is the focus of a separate manuscript (Manning unpublished data), and 4) modifying the SWAT model by manipulating changes in land-use and climate change to assess potential impacts of these changes to the yellow perch of Maumee Bay.

SWAT model: Data for SWAT Implementation

Spatial data that were used to create the SWAT model of the Maumee River basin included digital elevation maps (DEM), land use and land cover (LULC), soil type and climatological data. A DEM with a scale of 1:24000 (30 m DEM), and LULC data were retrieved from the Seamless Data Distribution System, National Center for Earth Resources Observation and Science (EROS), USGS (http://seamless.usgs.gov/) and processed using ArcGIS 9.3. The LULC were from the 2001 National Land Cover Data (NLCD). Soil data were from the State Soil Geographic (STASGO) database (UDSA ARS, 1991). Three weather stations located within the Maumee river basin were selected, and daily values for minimum and maximum air temperature (°c), and precipitation (mm/d) for each were obtained from the NOAA National Climatic Data Center (NCDC, http://ncdc.noaa.gov/).

Initial SWAT implementation

The specific model algorithms, parameters, and execution procedures for the implementation of SWAT models are provided in Santhi et al. (2001) and USDA-ARS (1999). For our model, the Maumee River basin was divided into 19 sub-watersheds (Fig. 2), and initial model calibration and sensitivity analysis were performed on the sub-watershed that included the gauging station located at Waterville, Ohio (USGS Stn #04193500), as this monitoring station has the most extensive daily data set available in the Maumee River basin. Daily stream flow (ft^3/s) and sediment concentration (mg/l) records for the Waterville station were retrieved from the USGS NWISWeb (http:// http://nwis.waterdata.usgs.gov/). Phosphorus concentrations (mg/l) were retrieved from the Heidelberg University National Center for Water Quality Research (http://www.heidelberg.edu/academiclife/distinctive/ncwqr/data/data). Model calibrations were performed on the hydrologic and phosphorus parameters for the years 1980 to 2010 and for the sediment parameters for the years 1980 to 2003. Simulations for our SWAT model were initiated from 1980, but that year was not included for comparison, as that year is used as a stabilization, or burn-in, period. After calibration, the model was extended to the entire Maumee River watershed, with the assumption that the adjoining sub-watersheds were similar enough in hydrologic response that the optimum parameter values identified in the initial calibration would be valid for these other sub-watersheds. The initial model implementation resulted in a flow, sediment, and nutrient regime for the Maumee River that represented historical conditions, and was used to verify the ability of the volumetric model and IBM to predict water clarity conditions, and ultimately yellow perch growth in the Maumee Bay. The fit between predicted and observed values for stream flow, phosphorus and sediment concentrations were assessed using the Nash Sutcliffe (NS) efficiency (Nash and Sutcliffe, 1970). Values for the NS efficiency vary from 1 for a perfect model fit, to 0 when the model prediction is no better than the average of observed values, as well as negative values when the model performs worse than the average observed values.

Volumetric model

In order to parameterize the IBM, we needed to estimate of daily sediment and phosphorus concentrations in the Maumee Bay. This was achieved by utilizing the daily output from the SWAT models to create a volumetric concentration model of the Maumee Bay. The model used a fixed volume for the bay of $83x10^6$ m^3 and the daily outflow of the Maumee River was considered equal to the volume of water that entered the bay. The primary input for water into the bay and the only source of sediment and phosphorus in the model was the Maumee River, with daily values for these parameters coming from the SWAT model. Even though it accounts for <2% of the volumne of water enetering Maumee Bay, we did include the 14,342 m^3/d average daily discharge for the Ottawa River as a a secondary input for water. Our predictions of sediment and phosphorus concentrations for the Maumee River output and thus the Maumee Bay varied daily. For simplification of modeling purposes, it was assumed that our calculated daily concentrations represented the entirety of the Maumee Bay (i.e. no diffusion time). These daily sediment and phosphorus concentration values were calibrated and corroborated using data collected in the field between 2002 and 2011 (Chaffin et al. 2012). Estimates from the model were compared to the corresponding dates from the field data, and it was found that the best-fit model for both sediment and phosphorus concentrations was achieved by taking the average of the estimated day and the 24 hour periods directly preceding and following the estimate (Fig. 3 A-B).

Individual Based Model

The daily sediment and phosphorus concentrations from the volumetric model were then used to parameterize an IBM previously developed for larval and juvenile yellow perch (Manning unpublished data). This model explicitly includes the effects of turbidity type and intensity based on laboratory-derived ingestion rates (Wellington et al. 2010) as opposed to encounter and consumption rates, which are traditionally calculated using swimming speed, light levels and prey densities (Fig. 4). Values for sediment concentration were able to be used directly in the IBM; however, phosphorus concentration and water temperature were used to calculate the timing and intensity of algal blooms. For years where bloom start dates are known (2002-2010), the observed data was used to set the timing of the switch to the algal feeding regime. For other years included in the model we needed to be able to estimate the start date of the bloom. To do this we used observed values of phosphorus concentrations, water temperatures and phytoplankton biovolume to identify environmental thresholds that best describe the onset of algal blooms. No blooms occurred when surface water temperatures were below 21°c or when phosphorus concentrations were below 0.05 mg/l. When both of these conditions were exceeded, mean algal biovolume was 153 ml/m^2. For use in our IBM, an algal bloom was considered to have started when both temperature and phosphorus concentrations exceeded these thresholds, and would end when either one or both dropped below their threshold values.

Our model simulated the daily ingestion and growth of larval and juvenile yellow perch through the first 124 days post-hatch. Each model run was initiated with a cohort of 10,000 individuals, and was repeated five times, for a total of 50,000 individuals. The daily records of individual length were averaged within each model run and then across the model runs to produce daily average cohort length values. To evaluate the performance of the model, we compared the model output, (mean length at 124 days post hatch) to data collected in the field by the Ohio Department of Natural Resources. This data set included the years 1981 to 2010, and individual years of data were considered for comparison to model estimates if they included fish length data from the last week of August and/or the first two weeks of September (approximately 124 days post-hatch). Average length of age-0 yellow perch at ~124 days post-hatch from the observation data were then compared to the length of individuals from the model using linear regression to determine the precision with which the model predicted growth of yellow perch in conditions that mimic natural temporal variations in turbidity type and intensity.

Increasing Urbanization SWAT model

In an effort to determine the impact of increasing urbanization in a predominately agricultural watershed, we created three models that increased the percentage of land use classified as urban (open /brownfield, low, med, and high density), by 10, 25 and 50% over the NLCD 2001 classifications. Land use within the basin was divided into three groups: agricultural, urban, and other. To simulate increasing urbanization in the basin, the percentage of the basin classified as "other" (wetlands, non-agricultural grassland/herbaceous, shrub/scrub, and forested) were reclassified as one of the four urban types, while the amount of agricultural land was maintained constant. When possible, the reclassification of cover type was done evenly within each group so as to preserve the relative percentage of each type. These models were run for the same time period as the initial model implementation, and used the optimum parameter estimates identified previously. Further increases in urbanization were not conducted because at a 50% increase in urbanization all land uses classified as "other" were reduced to 0% of the watershed, making it impossible to increase urbanization without reducing the percentage of agricultural uses.

The output from the increasing urbanization models were then used to inform the volumetric model and IBM in the same manner as described above. Average length of age-0 yellow perch at ~124 days post-hatch from each of the increasing urbanization scenarios were then compared to the estimate from the initial model implementation (0% change scenario), and each other using ANOVA and Tukey's Honest Significant Difference (HSD) test.

Climate Change SWAT Model

To model the effects of climate change in the Maumee River basin we used climatic predictions from the NOAA Geophysical Fluid Dynamics Laboratory's CM2Q-h1_SresA1B_x2 experiment. This data was accessed from the NOAA portal (http://nomads.gfdl.noaa.gov/dods-data/gfdl_cm2_1/CM2.1U-H3_SresA1B_X2/pp/atmos/). This experiment is on a global scale, and so only data from the grid that covers the Maumee River basin was used. Daily predictions for minimum and maximum air temperature, precipitation and atmospheric humidity for the years 2015 to 2025 were used to create three weather stations that took the place of the three original weather stations (Table 1). Because no flow or sediment values are available for these future time frames, the previously identified optimal flow and sediment parameters were used in this model.

The average mean length of age-0 yellow perch for each of the years included were then compared to the long term average of age-0 yellow perch length in the Maumee Bay from the initial model implementation, and to each other using ANOVA and Tukey's HSD to determine if there were any significant changes between the treatment groups as well as within the group.

RESULTS

Initial Model Implementation

Our initial model implementation showed that the SWAT model was able to accurately predict average daily stream flow, as well as phosphorus and sediment concentrations over an extended time period (Fig 3). The Nash Sutcliffe efficiency for stream flow was 0.845, sediment concentration was 0.771 and phosphorus concentration was 0.622. Additionally, our IBM of age-0 yellow perch growth in Maumee Bay was able to describe a over 70% of the observed variation in the data from the inter-agency trawls (Fig 5).

Increasing Urbanization

Increasing urbanization in the Maumee River watershed resulted in a significant reduction on average fish length in the Maumee Bay, but only when urbanization was increased by 50% (Fig. 6). The Tukey HSD test indicated that the 50% increase treatment was significantly different from the 0% and 10% increase treatments, but not the 25% increase, and the 25% increase was not significantly different from any of the other treatments (Table 2). Our model predicted a 10% increase in early season (Apr-Jun) flow volume from the Maumee River as urbanization in the watershed increased, but only a 1.7% increase in late season (Jul-Sept, Fig.7A). Additionally, the model predicted early season sediment loading in Maumee Bay to increase by 5%, and late season loading to increase by nearly 25% (Fig. 7B). This large increase in late season loading, with little change in overall flow volume leads to an 18% increase in average late season sediment concentrations in Maumee Bay (Fig.7C). The late-season increase in sediment concentrations in the 50% increase model reduced juvenile yellow perch prey consumption in the IBM by an average of 11%/fish/day, and resulted in a significant reduction in fish length at the end of the season.

Global Climate Change

Changes in temperature and precipitation due to Global Climate Change resulted in a predicted 10% reduction in average fish length over the eleven years included in this study (Fig. 8). Our model predicted that flow volume and sediment concentrations would display some year-to-year variation, but that there would be no significant trend through time for these water quality parameters (Fig.9 A and B). Late season phosphorus concentrations did rise over the years included in this model, however, phosphorus concentrations exceeded our bloom threshold in all years included (Fig. 10A). Average late season water temperatures, while displaying some year-to-year variation, increased by 4 to 5 degrees by the end of the model (Fig. 10B). The predicted increase in water temperatures in conjunction with the small increase in phosphorus concentrations lead to algal blooms starting between 1to 4 weeks earlier by the fourth year of the model (Fig. 11). Each additional week of algal bloom included in our model reduced fish growth by an average of 3% per week, and was the primary driver in the predicted reduction in fish length over the eleven years included.

DISCUSSION

As human populations continue to grow in coastal watersheds, the rate at which these systems are modified will increase rapidly. Whether it is through changes in land use, or changes in climate, the effects of human impacts will continue to alter how terrestrial and aquatic systems interact. The results of our study show that alterations in land use and climate in a watershed can alter the growth of age-0 fish in connected aquatic systems. These impacts are a result of the links between changes in sediment and nutrient run-off as well as temperature and sediment plume and algal bloom dynamics.

Increasing urbanization in the Maumee River watershed has the potential to alter the timing and intensity of sediment plumes in the Maumee Bay. In particular, high levels of urbanization may reduce sediment concentrations early in the season when yellow perch are in the pelagic larval stage of development, and increase late season sediment concentrations, when the yellow perch have become demersal juveniles. Previous studies have highlighted the importance of turbid river plumes for the growth and survival of larval fish (Grimes and Kingsford 1996). These studies suggest that a number of mechanisms may contribute to increased survival, including increased productivity and prey availability (Giovanni and Chester 1990), as well as reduced threat from larger, visual predators (Reichert et al., 2010). The predicted reduction in sediment concentrations during the larval phase of development may have the potential to both reduce growth and increase predation mortality of age-0 yellow perch in the Maumee Bay.

Any beneficial effects of a turbid river plume may not extend to the juvenile phase, however. The negative effects of decreasing water clarity become more pronounced as fish size increases, primarily due to the increased focal length of larger fish. Previous studies have shown that increasing turbidity can reduce the juvenile foraging ability of a number of fish species (DeRobertis et al. 2003), including yellow perch (Wellington et al. 2010). This reduction in feeding rate is demonstrated in our results that show a reduction of 11% in prey consumed by juveniles in the 50% increased urbanization model. Therefore, increasing urbanization in the Maumee River watershed has the potential to reduce fish growth by altering the timing and intensity of sediment plumes in the Maumee Bay.

The implications of our increasing urbanization scenarios are two-fold. First, these models show that increasing urbanization has the potential to reduce age-0 yellow perch growth through the alteration of the timing and intensity of sediment plumes. The second is that in an agriculturally dominated watershed, such as the Maumee River basin, the hydrologic and sediment inputs from agricultural runoff is so influential that it may require the complete elimination of wetlands, forested areas and other buffers zones to see any significant change in flow volume and sediment concentrations in the connected aquatic systems.

The Global Climate Change scenario shows that predicted changes in temperature and precipitation in the Maumee River watershed could lead to significant reductions in the growth of age-0 yellow perch in Maumee Bay in as little as ten years. This predicted reduction in growth is primarily driven by an increase in summer water temperatures, which promote an earlier onset, and increased duration of algal blooms. Increasingly frequent and intense algal blooms have become more common in a number of coastal regions (Hallegraff, 1993; Anderson et al., 2002; Rinato-Kanto et al., 2005; Chaffin et al., 2011), and the results of this study suggest that these blooms could become more severe in the future. This is particularly concerning as algal turbidity has been linked to increased fish mortality and reduced condition of fish (Burkholder 1998; Malakoff 1998; Kempton et al. 2002). In juvenile yellow perch, Wellington et al. (2010) showed that prey consumption was significantly lower in algal than in sediment turbidity across all turbidity levels, while the negative effects for larvae were only apparent at high turbidity levels. This is an important distinction, as the seasonal timing of sediment plumes and algal blooms exposes juveniles more predominately to algal driven turbidity.

Our project highlights the interactions between terrestrial and aquatic systems. In particular, this study shows how changes in land use and climate in a watershed can significantly reduce the growth of a fish species in an associated water body through alteration of the visual environment. The results of this study can be helpful in understanding how potential modifications to a watershed may have unintended consequences downstream.

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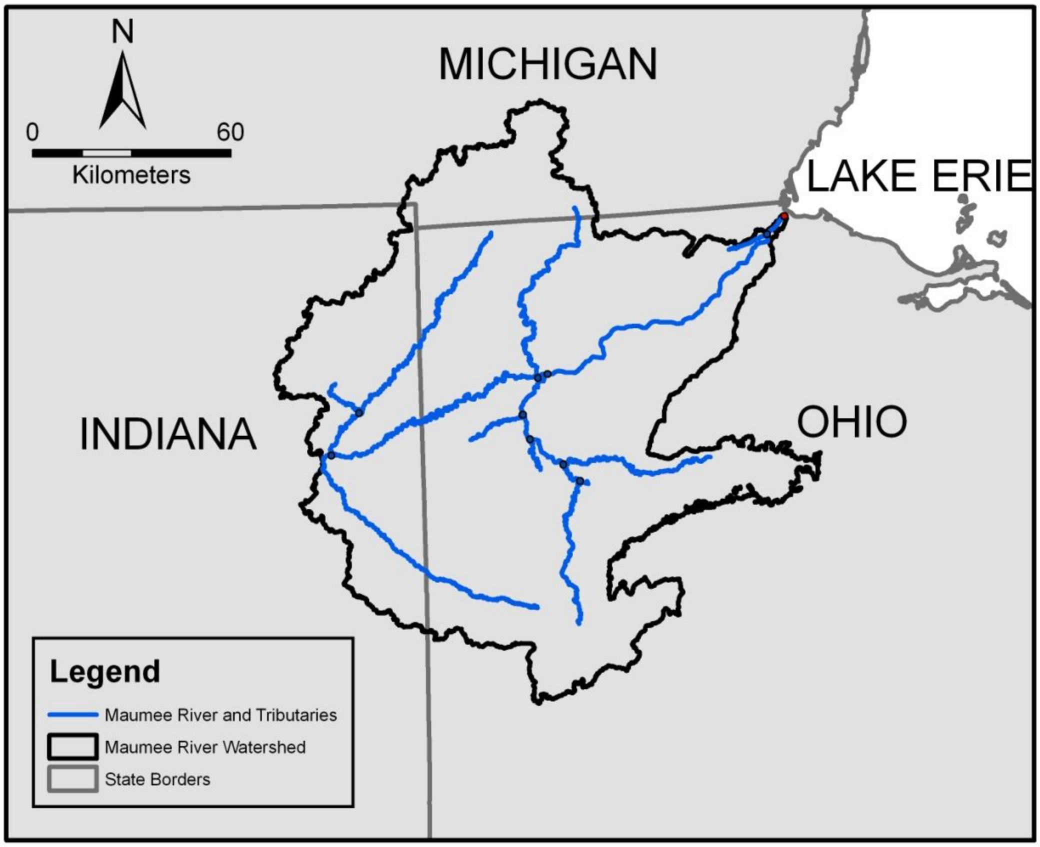

Figure 1: Map of the Maumee River watershed, including the main branch, as well as the major tributaries. The Maumee River flows northeast from the confluence of the St. Mary's and St. Joseph's rivers near Ft. Wayne, Indiana. The River empties into the Maumee Bay, Lake Erie at Toledo, Ohio.

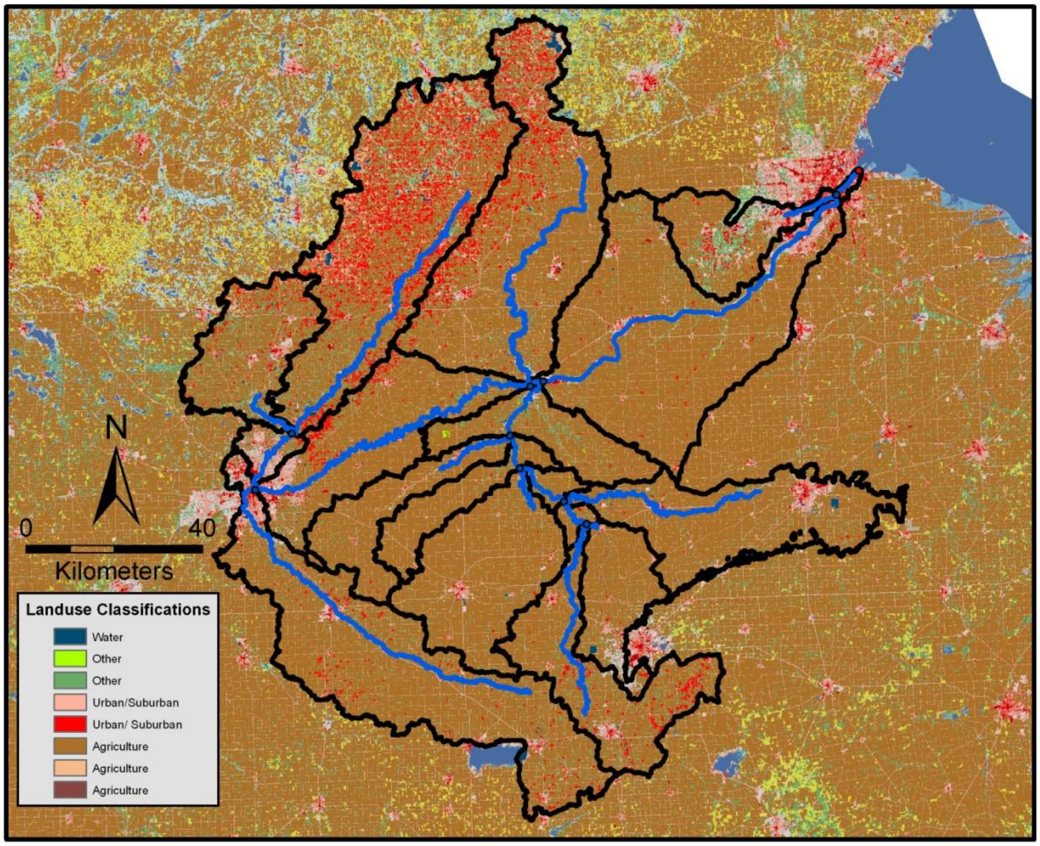

Figure 2: Land use classification map of the Maumee River watershed, including the main basin and the 19 subwatersheds included in this study.

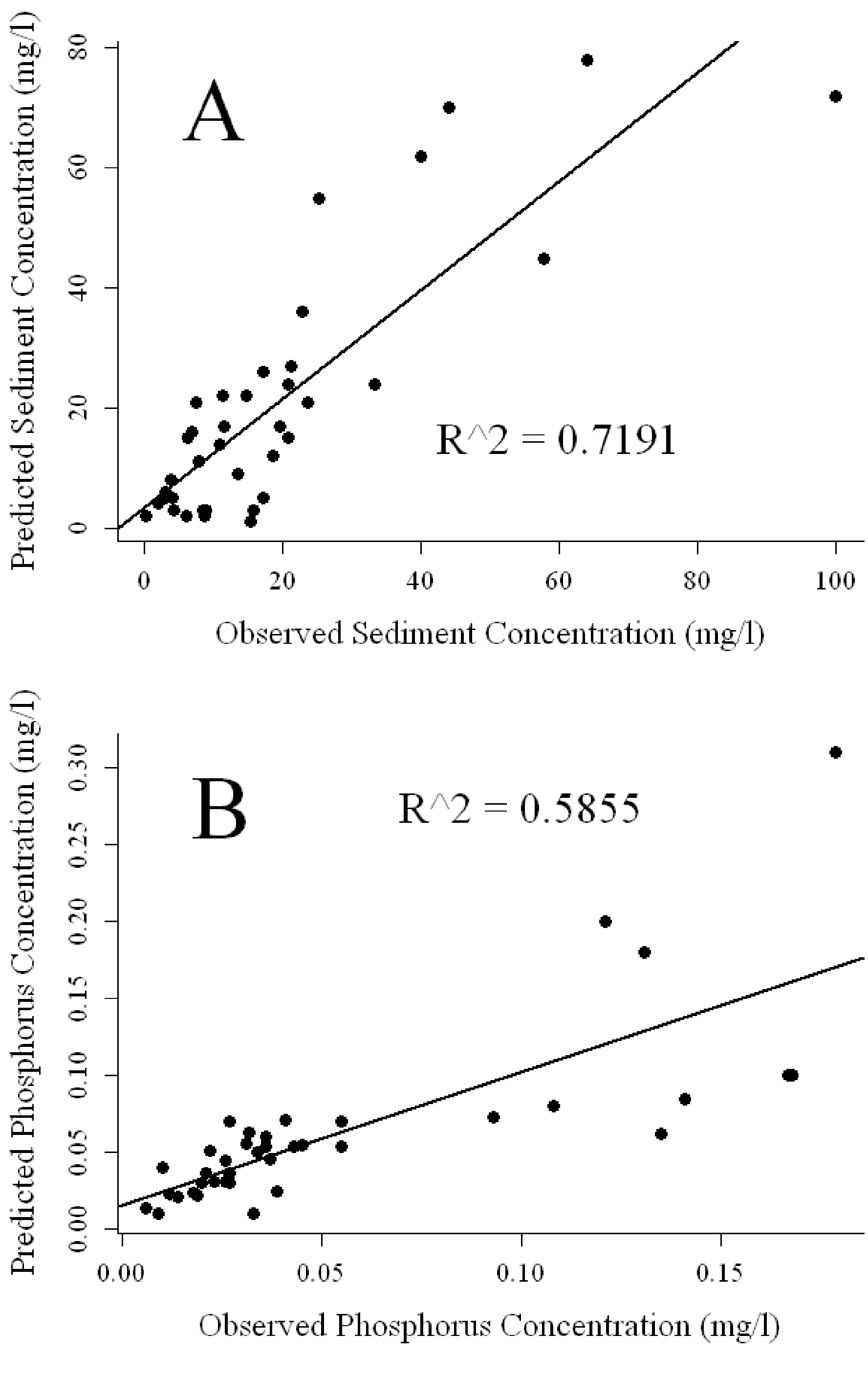

Figure 3: Linear regressions of observed and predicted A) Sediment concentrations and B) Phosphorus concentrations from the volumetric model of Maumee Bay

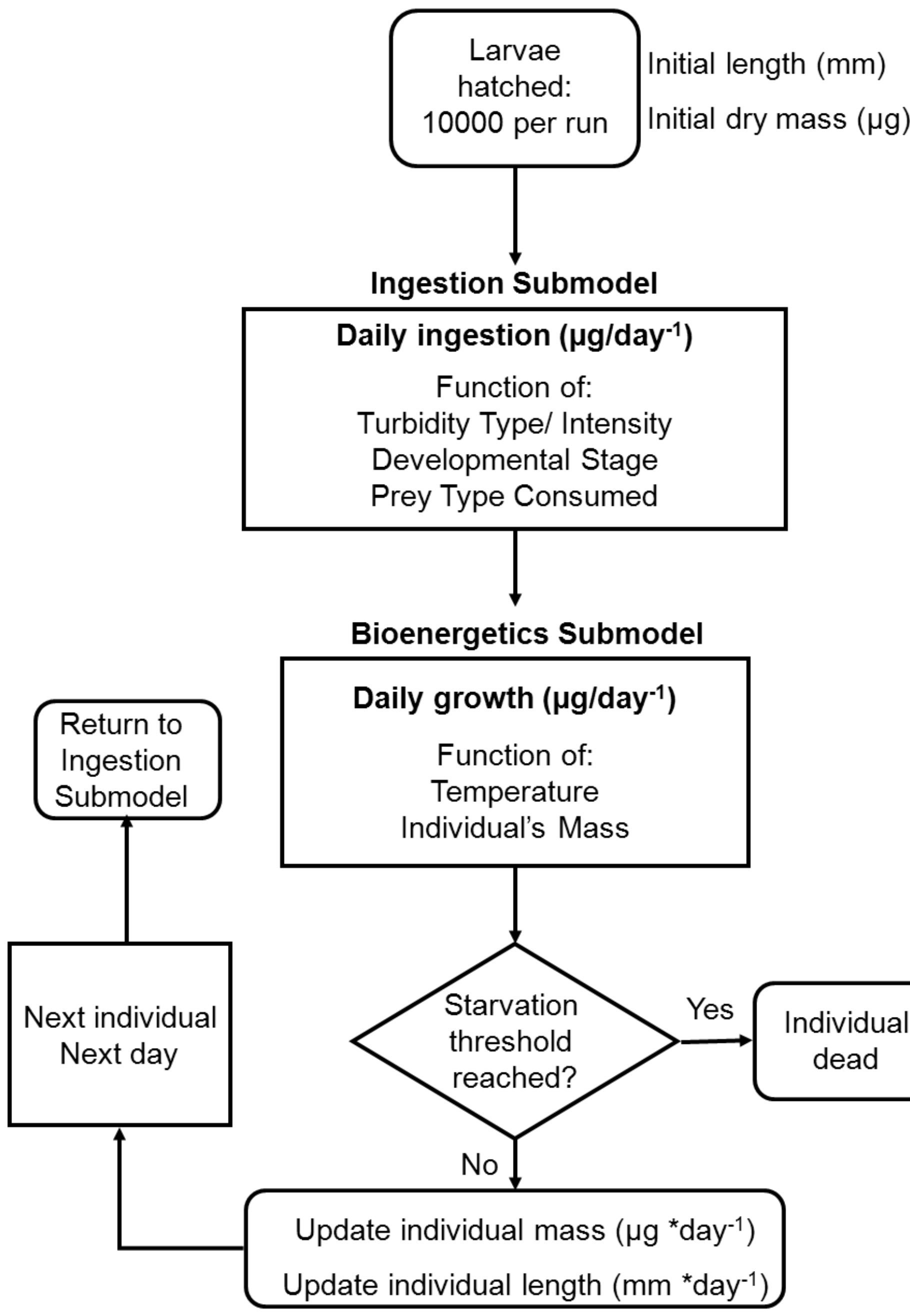

Figure 4: Flow diagram of the Individual Based Model showing primary submodels and included parameters (Manning unpublished).

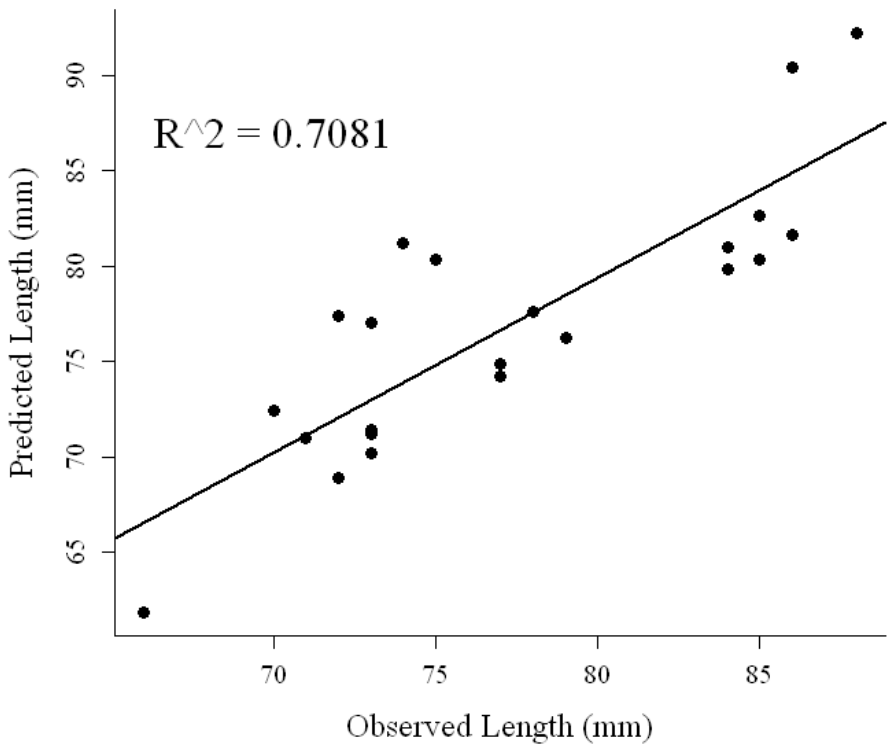

Figure 5: Linear regression of the observed age-0 yellow perch lengths from the multi-agency trawl data and predicted lengths 124 days post-hatch from our Individual Based Model.

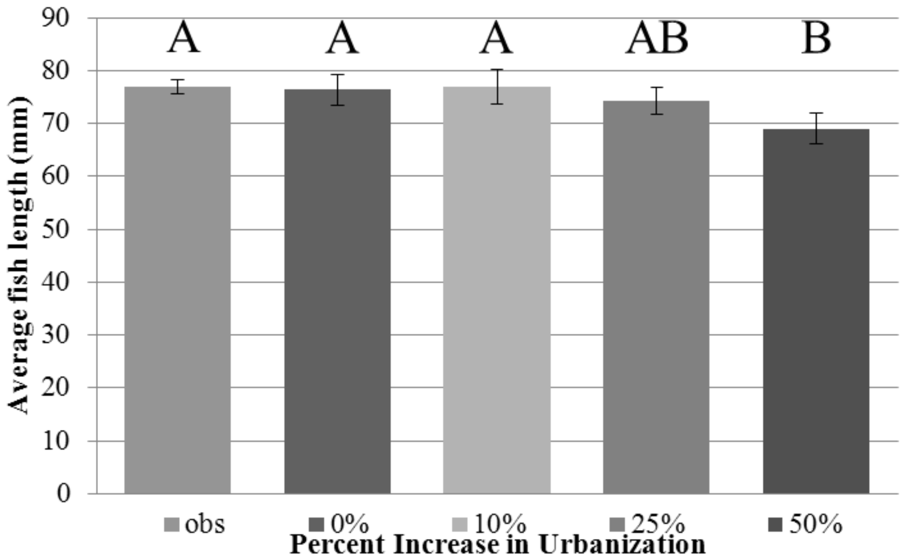

Figure 6: Average fish length 124 days post hatch for the four urbanization treatments, as well as the observed fish lengths from the multi-agency trawl data. Error bars are +/- 1 s.e. Letters denote significant differences between treatments.

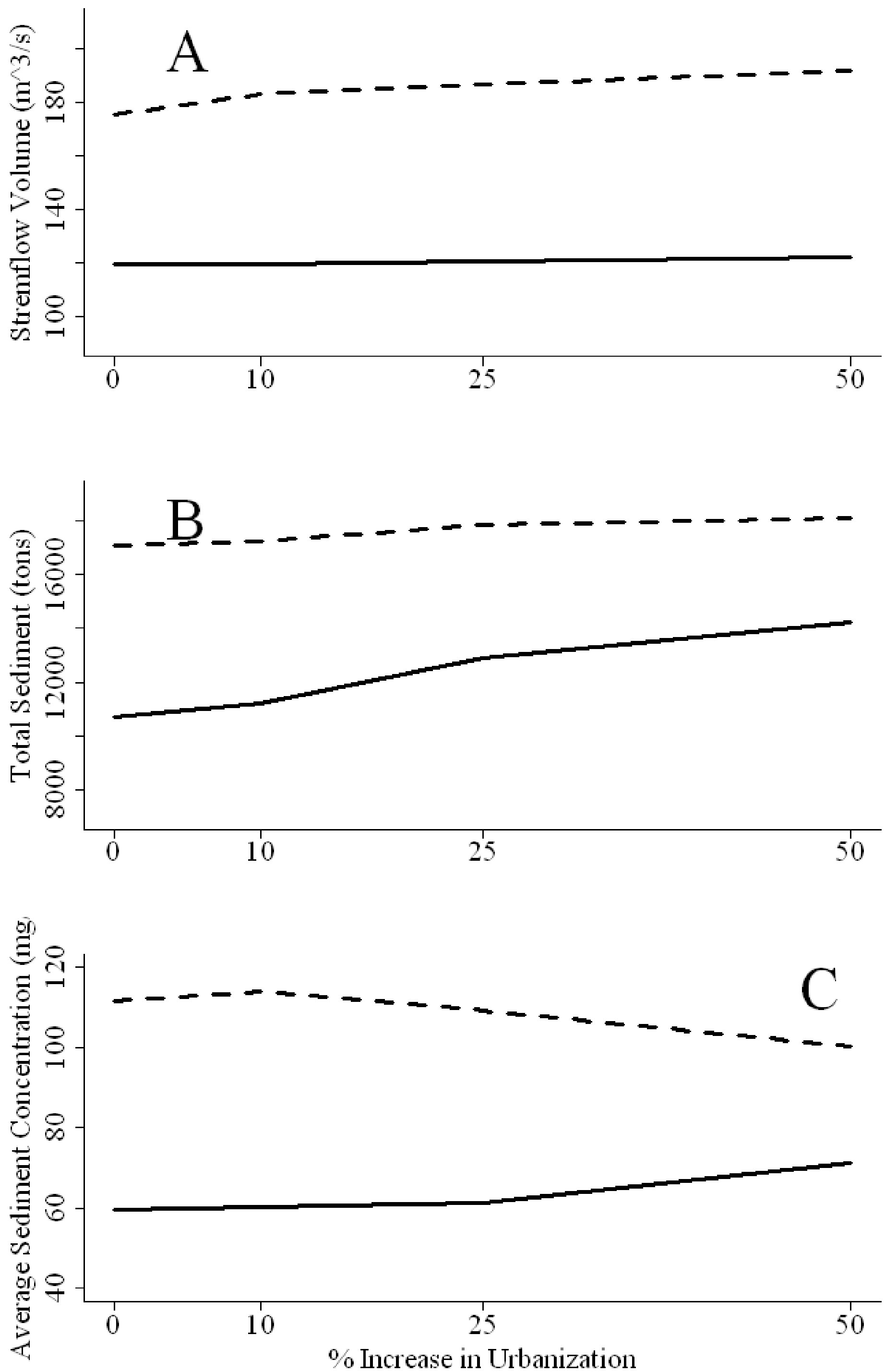

Figure 7: Changes in A) Maumee River stream flow, B) total sediment transport and C) average daily sediment concentration in the Maumee Bay for both early (Apr-Jun) and late (Jul-Sept) seasons based on our models of changes in urbanization.

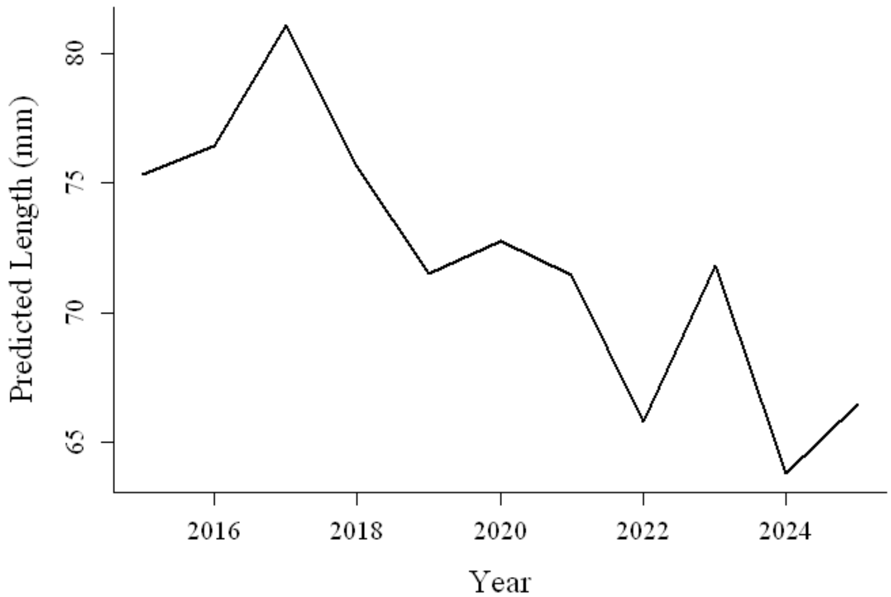

Figure 8: Change in the predicted average length of age-0 yellow perch 124 days post hatch for the years included in the GCC model.

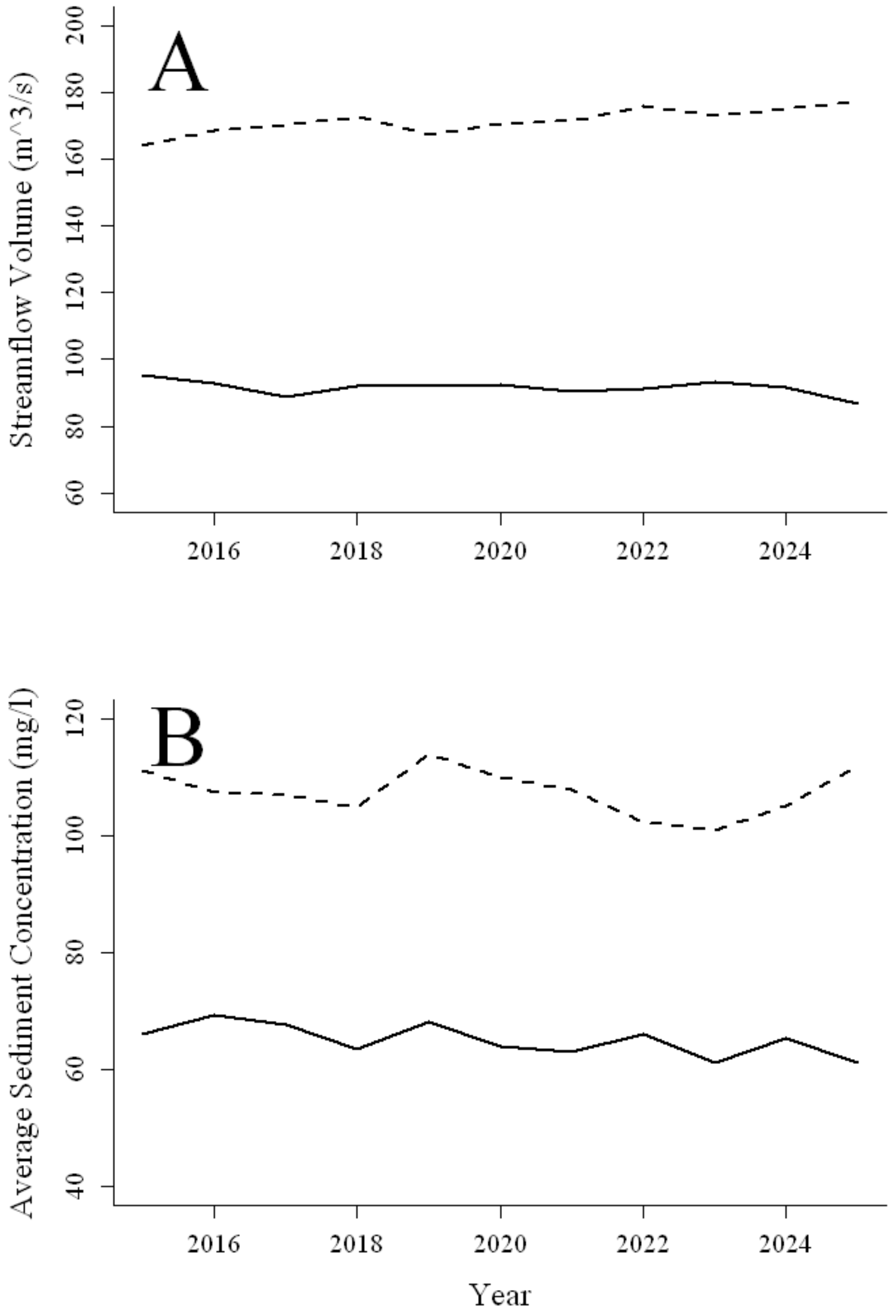

Figure 9: Changes in A) average daily Maumee River streamflow and B) the average daily sediment concentrations in the Maumee Bay in early and late season for the years included in the GCC model.

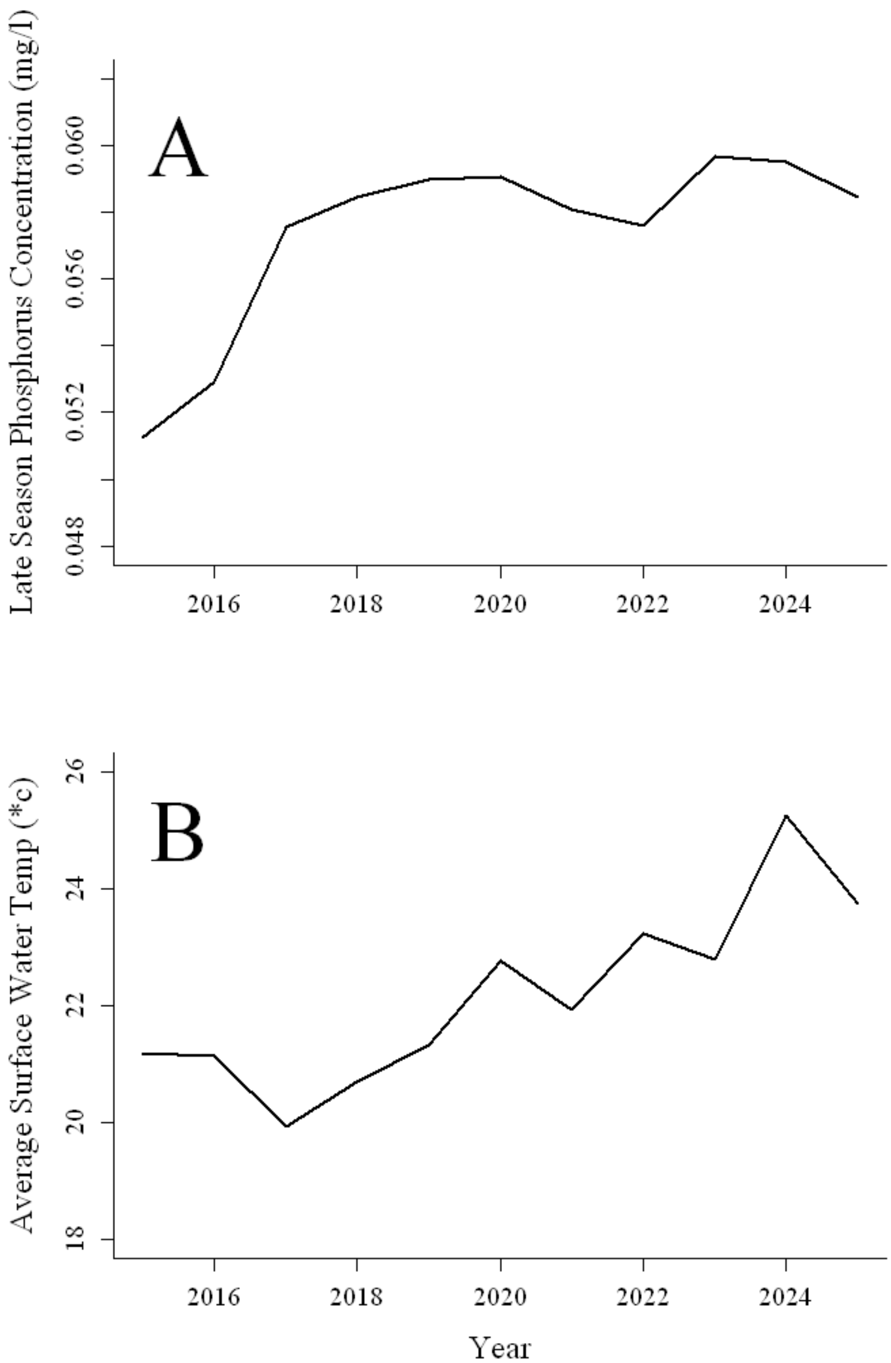

Figure 10: Result of our GCC model showing: A) late season phosphorus concentrations in the Maumee Bay, and B) average late season surface water temperatures in Maumee Bay.

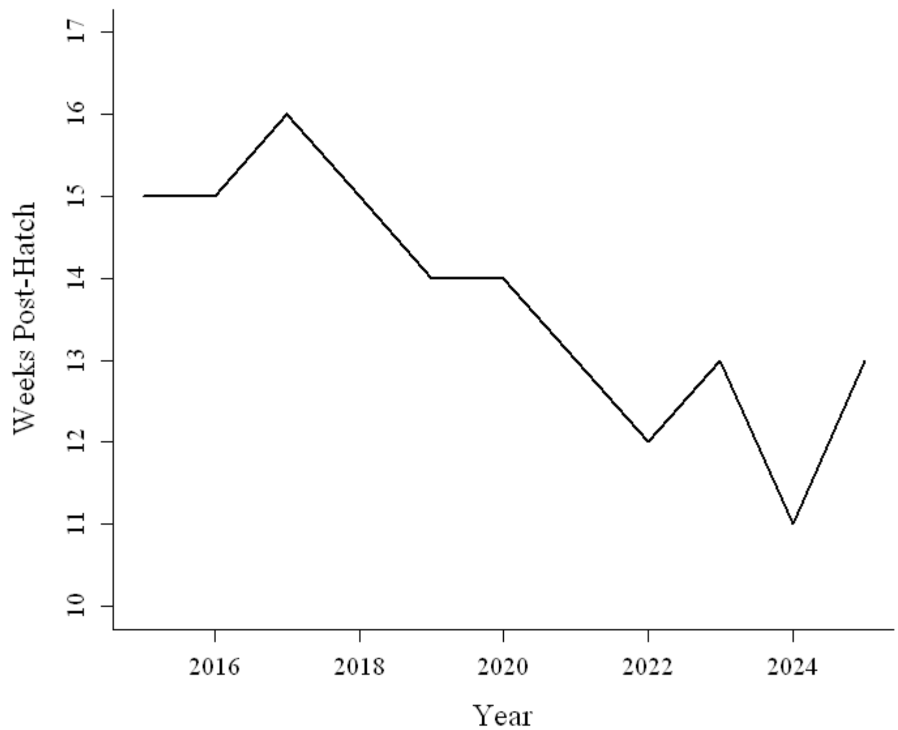

Figure 11: The change in number of weeks post hatch in which a bloom was predicted to start for the years included in the GCC model.

Table 1: Tukey's HSD comparison table for the treatments used in the urbanization models. An adjusted p-value < 0.05 indicates a significant difference between treatments.

Treatment Comparisons	Mean Difference	95% Confidence Interval		Adjusted p-value
		Lower Bound	Upper Bound	
0% - 10%	0.625	-5.12	6.37	0.998
0% - 25%	-2.125	-7.87	3.62	0.843
0% - 50%	7.292	1.55	13.03	0.006
10% - 25%	-2.750	-8.49	2.99	0.674
10% - 50%	7.917	2.18	13.66	0.002
25% - 50%	5.167	-0.57	10.91	0.099