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Research papers

Assessing the relative importance of parameter estimation in stream health based environmental justice modeling

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ABSTRACT

Performance of environmental justice models depends on the level of accuracy in measuring or estimating the health of the environment. In the past decades, and especially in the area of stream health modeling, significant improvement has been observed. However, the impacts of these improvements on the robustness of environmental justice models have not been evaluated. Therefore in this study, the relative importance of parameter estimation in stream health based environmental justice modeling was evaluated. The Saginaw River Basin in Michigan was considered as the study area, and four major ecological indices evaluating the response of fish and macroinvertebrates to instream stressors were used for stream health assessment. Seventeen socioeconomic and physiographic indices were evaluated at three census levels of county, census tract, and block group. Then the ecological, socioeconomic, and physiographic indices were used in the development of stream health based environmental justice models. Results showed that incorporating ecologically relevant indices and a using two-phase modeling approach not only improved the performance of stream health predictive models but also reduced the sensitivity of environmental justice models to aggregation at different census levels. In addition, using improved stream health indices reduced the redundancy of the independent variables (socioeconomic and physiographic indices), where the total number of significant parameters was reduced from 171 to 115. Besides that, more robust and meaningful spatial dependencies were observed among stream health measures and environmental justice parameters at different spatial levels. In summary having a reliable stream health information is the key for development of robust environmental justice models as evidence by improving model predictability and eliminating contradictory results compared to previous studies.

1. Introduction

Anthropogenic activities have degraded natural resources which in turn also threatens human ecosystems due to the interwoven nature of natural and human system interactions (Liu et al., 2007; Carpenter et al., 2009; Alberti et al., 2011). However, degraded environments do not equally affect various groups in society and some communities such as low income and people of color are more vulnerable to environmental hazards than other groups (Massey, 2004; Downey and Hawkins, 2008). Therefore, the concept of Environmental Justice was introduced to provide fair treatment and involvement of all social groups in implementation and enforcement of environmental laws and regulations (U.S. EPA, 2014). In other words, the aim of environmental justice is providing equal access to healthy environments as right for all people.

Water is one of the environmental resources that is considered in the environmental justice studies. In the U.S., the traditional approach for water resources assessment was mainly focused on water quality and physical characteristics. However, a nationwide assessment of riverine ecosystems that was performed by the U.S. Environmental Protection Agency (U.S. EPA) found that despite all implemented water quality regulations, still more than 40% of nation's streams were in poor biological condition (U.S. EPA, 2015). Therefore, a new criterion called Biological Integrity Assessment was introduced in which the physical, chemical, and biological characteristics of streams should be simultaneously considered to improve the overall assessment of water resources (U.S. EPA, 2011; U.S. EPA, 2015; Woznicki et al., 2015). This was achieved by the introduction of stream health indices, which quantify the response of aquatic species to instream stressors (Herman and Nejadhashemi, 2015; Van Metre et al., 2017). However, monitoring stream health indices in a large area is both expensive and time consuming. Therefore, modeling approaches have been used to estimate

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stream health indices (Woznicki et al., 2016a).

The general inputs to these models are landscape features and in instream water quantity and water quality parameters (Miserendino et al., 2011; Einheuser et al., 2012). Traditionally, linear regression (Frimpong et al., 2005; Pont et al., 2009; Moya et al., 2011) and multivariate techniques (Simpson and Norris, 2000; Aguiar et al., 2011) were used for stream health model development. Later nonlinear techniques such as Fuzzy Logic (Adriaenssens et al., 2006; Marchini et al., 2009), Artificial Neural Network (ANN) (Lencioni et al., 2007; Mathon et al., 2013), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) (Einheuser et al., 2012, 2013) were used to improve model predictabilities. Despite all of these improvements, the predictive power of stream health models is moderate mainly due to the complexity of natural systems (Woznicki et al., 2015). Meanwhile, further improvements were achieved when in the early 2010s, Poff and Zimmerman (2010) highlighted the importance of flow alteration on ecological response. In particular, the magnitude, frequency, duration, timing, and rate of change of flow are master variables that affect aquatic species (Poff et al., 1997; Olden and Poff, 2003; Poff and Zimmerman, 2010). Therefore, several tools such as the Hydrological Index Tool (HIT) (USGS, 2017), EflowStats (Archfield et al., 2014), and MATLAB Hydrological Index Tool (MHIT) (Abouali et al., 2016a) were developed to incorporate ecologically relevant hydrological indices. Studies showed that these indices significantly improved the accuracy of stream health predictive models (Herman et al., 2015; Herman et al., 2016; Abouali et al., 2016b).

One of the applications of steam health models is to describe the environmental conditions that impact human well being and therefore relate to the concept of environmental justice. As a result, the concept of biological integrity assessment has recently been introduced in environmental justice studies through integration of stream health models. Sanchez et al. (2014) used spatial regression models and bivariate mapping to find vulnerable social communities. They used four common stream health indices (for fish and macroinvertebrates), and nine socioeconomic indices (representing education, housing, income, population, and race) collected at the census tract level. The results were promising and showed high correlations between regions with the lowest stream health status and vulnerable social communities (Sanchez et al., 2014). Sanchez et al. (2015) also introduced spatial clustering, which improved the predictability of environmental justice models. Daneshvar et al. (2016) further improved the model predictabilities through the introduction of multilevel socioeconomic and physiographic census information. However, all three studies (Sanchez et al., 2014, 2015; Daneshvar et al., 2016) used the same nonlinear stream health modeling approach. These studies showed relationships between stream health indices and socioeconomic variables; however, in several cases, these relationships were either very weak or contradictory. Therefore, there is a need to explore the cause of these deficiencies.

As described earlier, the variability in the stream health model performance can introduce a large level of error on stream health based environmental justice models. However, new developments in stream health modeling, such as the two-phase approach (Abouali et al., 2016b), has resulted in significant improvement in the overall predictability for both fish and macroinvertebrate based stream health models. Therefore, the goal of this study is to assess the relative importance of parameter estimation in stream health based environmental justice models by comparing the results against previous studies. Our hypothesis was that more accurate stream health predictions would result in the development of more robust environmental justice models in which spatial dependencies among biological and socioeconomic characteristics at different spatial levels would be revealed. In order to examine this hypothesis, we tested three objectives considering results from former and current stream health models by comparing the level of: 1) interdependence between stream health indices and socioeconomic and physiographical parameters, 2) spatial dependency for single level environmental justice models and 3) improvement for multilevel environmental justice models.

2. Materials and methods

2.1. Study area

The Saginaw River Basin, which is located in the state of Michigan, U.S.A. was selected as the study area (Fig. 1). With the total drainage area of more than 16,000 km^2, it is the largest watershed in Michigan and drains to Lake Huron. Agricultural lands are the dominant landuse (36.2%), followed by forest (24.8%), wetland/lake (14.3%), pasture (12.4%) and urban (12.3%) lands. The U.S. EPA identified the Saginaw River and Bay as an area of concern due to degraded fisheries, sediment pollution, and loss of recreational values (U.S. EPA, 2017). Agricultural and urban runoff, industrial discharges, and sewer overflows are some major sources of pollution in this region (U.S. EPA, 2017). With more than 7,000 miles of streams, the Saginaw River Basin provides a wide range of habitats for fish and other species (WIN, 2017). It also addresses the needs for drinking water, electrical power generation, and industrial consumption in this region (WIN, 2017). According to the U.S. Census Bureau (2010), the Saginaw River Basin is home of almost 1.5 million people, where 49% are men and 51% are women. The majority of residents are young and more than 52% of them are in the range of 25 to 65 years old, 34% are under 25 years old, while only 14% are senior (above 65 years old). More than 85% of population is white, followed by African American (10%), while other races are less than 5%. The Saginaw River is also a key shipping transit in Mid-Michigan that connects two cities, Saginaw and Bay City. Flint is another big city in this region that has faced water contamination problems (U.S. EPA, 2013).

2.2. Stream health indices

Four common stream health indices including: (1) the Index of Biotic Integrity (IBI) for fish, and (2) the Hilsenhoff Biotic Intex (HBI), (3) Family Index of Biotic Integrity (FIBI), and (4) Ephemeroptera, Plecoptera, Trichoptera (EPT) index for macroinvertebrates were used in order to assess the biological integrity of riverine ecosystems. The IBI is a multi-metric index, first developed in the 1980 s, that evaluates stream conditions by measuring 12 metrics that describe the species richness, abundance, and trophic composition of fish communities (Karr, 1981; Kerans and Karr, 1994) These metrics are given individual scores that are summed to calculate an overall measure of stream health with score ranges from zero (poor condition) to 100 (pristine condition) (Herman and Nejadhashemi, 2015). Meanwhile, the HBI, first developed in the 1970 s, evaluates stream conditions with respect to organic pollution by identifying all of the taxa found in the stream and determining their tolerances to organic pollution (Hilsenhoff, 1987). After identifying all taxa present, an average score is calculated with scores ranging from zero (pristine condition) to 10 (poor condition) which is used to classify organic pollution based stream degradation (Hilsenhoff, 1987). The FIBI, first developed in the 1990 s, is the third index used in this study and is a multi-metric stream health index based on the IBI (Kerans and Karr, 1994). Unlike the IBI though, the FIBI evaluates stream conditions by evaluating the response of macroinvertebrate communities to industrial pollutants by measuring 13 metrics that describe the species richness, abundance, and trophic composition of macroinvertebrate communities (Kerans and Karr, 1994). Similar to the IBI, these metrics are scored individually and then aggregated to produce an overall stream health score with scores ranging from zero (poor condition) to 45 (pristine condition) (Woznicki et al., 2015). The final stream health index used in this study was the EPT index, which was first developed in the 1980s (Lenat, 1988). This index utilizes the sensitivity of three macroinvertebrate orders, namely Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), to