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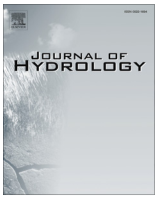

Evaluating stream health based environmental justice model performance at different spatial scales

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SUMMARY

This study evaluated the effects of spatial resolution on environmental justice analysis concerning stream health. The Saginaw River Basin in Michigan was selected since it is an area of concern in the Great Lakes basin. Three Bayesian Conditional Autoregressive (CAR) models (ordinary regression, weighted regression and spatial) were developed for each stream health measure based on 17 socioeconomic and physiographical variables at three census levels. For all stream health measures, spatial models had better performance compared to the two non-spatial ones at the census tract and block group levels. Meanwhile no spatial dependency was found at the county level. Multilevel Bayesian CAR models were also developed to understand the spatial dependency at the three levels. Results showed that considering level interactions improved models' prediction. Residual plots also showed that models developed at the block group and census tract (in contrary to county level models) are able to capture spatial variations.

1. Introduction

Human and natural ecosystems are interconnected and affect one another. Studies show that human activities can substantially alter ecosystems, changing biological diversity, land surface, and other resources that often have long-term environmental effects (Skole and Tucker, 1993; Vitousek et al., 1997; Halpern et al., 2008; Einheuser et al., 2013a). Anthropogenic activities have changed more than one-third of land surfaces (Vitousek et al., 1997; Allan, 2004). Halpern et al. (2008) reported that no marine ecosystem has been left untouched by human activities, while more than forty percent of these ecosystems have faced notable changes. Fresh water contamination is one of the more apparent impacts of human interventions, which also negatively affects human health (Smith et al., 1999; Pomati et al., 2006; Vairavamoorthy et al., 2007; Vörösmarty et al., 2010; Harwood et al., 2014; Barnhoorn et al., 2015) through waterborne diseases such as diarrhea, cholera, SARS, and hepatitis (Levine et al., 1990; Wu et al., 1999; Ashbolt, 2004; Mieiro et al., 2009). Therefore, sustaining healthy streams can be beneficial to both human and natural systems.

A healthy stream is a stream that is sustainable and resilient, while maintaining both societal and ecological necessities (Meyer, 1997; Welsh and Hodgson, 2008; Walsh et al., 2016). In order to evaluate stream health conditions, biological indicators are used to quantify the ecological integrity of river systems (Cairns and Pratt, 1993; Jackson and Füreder, 2006; Dijk et al., 2013; Herman et al., 2015; Woznicki et al., 2016). In other words, biological indicators represent aquatic communities' response to human and natural disturbances (Barbour et al., 1999; Flinders et al., 2008). Fish and macroinvertebrates are commonly used for the development of biological indicators (Meyer, 1997; Hering et al., 2006; Wang et al., 2007; Walters et al., 2009; Holguin-Gonzalez et al., 2013; Muñoz-Mas et al., 2014). Macroinvertebrates are used for assessing local habitat conditions due to limited mobility, while fish are often used for large-scale stream health assessment because of seasonal migrations within stream systems

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(Karr, 1981; Lenat, 1988; Plafkin et al., 1989; Lammert and Allan, 1999; Young et al., 2000; Herman and Nejadhashemi, 2015).

On the contrary, unhealthy streams negatively affect ecosystem services that ultimately influence human well-being, social health, and access to resources (Corvalan et al., 2005; Schwarzenbach et al., 2010; Azizullah et al., 2011; Katukiza et al., 2014). However, the levels of influences are different between racial or ethnic groups, in particular minorities and low-income communities are generally more affected (Pollock and Vittas, 1995; Helfand and Peyton, 1999; Gwynn and Thurston, 2001; Taylor, 2014; Kim, 2015). In order to address these issues, the concept of 'Environmental Justice' was introduced that deals with the fair distribution of resources to all people regardless of race, color, national origin or income (EPA, 2015a). Therefore, environmental justice by nature deals with different elements that vary across space, time and organizational units (Pickett et al., 2005; Liu et al., 2007; An, 2012). Compared to 'Environmental Equity', which aims to evenly distribute risks among population from environmental degradations, environmental justice aims to eliminate those risks especially within the vulnerable population such as minorities and lower class people (Cutter, 2012; Brulle and Pellow, 2006; Ewall, 2012). Therefore, environmental justice became a key factor in public health studies (Lee, 2002; Brulle and Pellow, 2006; Holifield, 2012; Wolch et al., 2014). Many environmental justice studies are done with respect to air pollution (Jerrett et al., 2001; Maantay, 2007; Gilbert and Chakraborty, 2011; Zou et al., 2014), while a few studies (e.g. Sanchez et al., 2014, 2015) have used biological indicators in order to evaluate environmental justice with respect to stream health integrity.

While both environmental and socioeconomic data can be collected at different scales, studies have shown that the scale of study plays an important role in the analysis and using the wrong scale can be misleading (Wilson et al., 1999; Maantay, 2007; Silver, 2008; Maantay and Maroko, 2009). For example, while census tract is the most commonly used in environmental justice studies (Jerrett et al., 2001; Corburn et al., 2006; Gilbert and Chakraborty, 2011; Sanchez et al., 2014, 2015), socioeconomic data are also collected at county, block group, and census block scales (U.S. Census Bureau, 2010).

Zimmerman (1993) reported that using jurisdictional boundaries, such as counties, results in different environmental equity results compared to non-jurisdictional boundaries, such as census tract (Zimmerman, 1993). Fisher et al. (2006) studied air toxic pollution (point source) in the context of environmental justice and across various spatial levels (census tract, block group, and census block). They concluded that using census tract data is not a proper scale for a point source pollutants study, since it assumes uniform distribution of pollutant and population among census tracts, regardless of their size or shape (Fisher et al., 2006). Zou et al. (2014) used socioeconomic data at three spatial levels (zip code, census tract and block group) in an environmental justice study in the context of sulfur dioxide exposure. Using whites as a reference for racial inequality analysis, they showed that not only pollutant source (e.g. industrial or vehicle) but also spatial scale (e.g. county or census tract) affect final outcomes. For example, less exposure to pollutants was reported at the block group level compared to the zip code and census tract levels in black populations. In general, more reliable results were obtained at the smallest spatial scale, which was the block group (Maantay, 2007). Apart from that, multilevel analysis has been shown to produce better predictions than single level analysis in public health studies (Geronimus and Bound, 1998; Pickett and Pearl, 2001; Krieger et al., 2002a; Arcaya et al., 2012). For example, Geronimus and Bound (1998) showed that multilevel analysis measures of health data collected at the zip code and census tract levels outperform health outcome predictions compared to single level analysis. Similarly, using composite socioeconomic data collected at the zip code, census tract, and block group levels, improved the measures in mortality and cancer incidence studies (Krieger et al., 2002a). Arcaya et al. (2012) also showed that considering multilevel dependency between the U.S. life dataset of 1999 at different scales (county, state, and region) improved projection of the life expectancy pattern (Arcaya et al., 2012).

The goal of this study is to evaluate the effects of spatial data resolution on environmental justice analysis with respect to stream health integrity. We hypothesis that the environmental justice analysis using socioeconomic data at the block group level is the most reliable and will capture more spatial dependency between socioeconomic and environmental (stream health) parameters compare to census track and county levels. We also hypothesis that considering multilevel dependency between socioeconomic data may improve the predictably of the environmental justice models. This study is unique since to the best of knowledge no study has considered both the effects of socioeconomic spatial resolutions and multilevel interactions in the context of stream health. The specific objectives are to: (a) measure the degree of dependency between stream health indicators and control parameters across the three spatial scales (county, census tract, and block group); (b) understand the spatial dependency at the three levels and among stream health indicators and control parameters using regression analysis; and (c) evaluate the importance of multilevel analysis in improving the environmental justice model predictability.

2. Methodology

2.1. Study area

The study area is the Saginaw River Basin, the largest six-digit hydrologic unit located in Michigan. Each hydrologic unit is identified by a unique hydrologic unit code (HUC). The HUC for the Saginaw River Basin is 040802. The study area contains six hydrologic units Tittabawassee (04080201), Pine (04080202), Shiawassee (04080203), Flint (04080204), Cass (04080205) and Saginaw (04080206), which drains to the Lake Huron (Fig. 1a). The size of study area is 16,120 square kilometers. Approximately, half of the study area is agricultural land, mostly covered by corn and soybean, 25% is forestlands, while developed areas, wetlands, rangeland, and surface water cover the rest.

Increase in soil erosion, contaminated sediment, and nutrients, has degraded aquatic life and recreational values in the study area to the extent that the US Environmental Protection Agency (EPA) has identified the Saginaw River as an area of concern in the Great Lakes basin (EPA, 2015b).

2.2. Stream health indicators

In order to evaluate stream health, four biological indicators, which represent macroinvertebrates and fish abundance, were used in this study (Karr, 1981; Lenat, 1988; Hilsenhoff, 1987; Lyons, 1992; Kerans and Karr, 1994; Sponseller et al., 2001; Infante et al., 2008; Einheuser et al., 2012; Einheuser et al., 2013b). The first indicator is the Index of Biotic Integrity (IBI); it describes a series of fish measures such as species richness and composition, trophic composition, abundance and condition that are evaluated by a numeric score that ranges from 0 to 100 (Karr, 1981; Kerans and Karr, 1994; Herman and Nejadhashemi, 2015). The lower scores represent high level of stream disturbance and vice versa. The Hilsenhoff Biotic Index (HBI) is a common macroinvertebrate indicator, which represents tolerance values of organic pollution within different species. It is varied from 0 to 10, where