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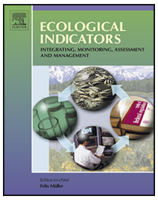

Large-scale climate change vulnerability assessment of stream health

Sean A. Woznicki[a], A. Pouyan Nejadhashemi[a,*], Ying Tang[b], Lizhu Wang[c]

[a] Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, MI, United States
[b] Department of Geography, Michigan State University, East Lansing, MI, United States
[c] International Joint Commission, Great Lakes Office, Windsor, ON N9A 6T3, Canada

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ABSTRACT

Freshwater streams are critical resources that provide multiple benefits to humans and aquatic biota alike. As climate changes, it is projected that changes to the hydrological cycle and water temperatures will affect individual biota and aquatic ecosystems as a whole. The goal of this study was to determine the extent of climate change impacts on stream ecosystems as represented by four commonly used stream health indicators (Ephemeroptera, Plecoptera, and Trichoptera taxa (EPT), Family Index of Biotic Integrity (FIBI), Hilsenhoff Biotic Index (HBI), and fish Index of Biotic Integrity (IBI)). Seven watersheds in Michigan were selected based on stream thermal regimes. The Soil and Water Assessment Tool was used to simulate streamflow and pollutant loads. Important variables for each thermal class were selected using a Bayesian variable selection method and used as inputs to adaptive neuro-fuzzy inference systems models of EPT, FIBI, HBI, and IBI. Finally, an ensemble of climate models from the Coupled Model Intercomparison Project Phase 5 were used to determine the impacts of climate on the stream health in 2020–2040 compared to 1980–2000. The risk of declining stream health was determined using cumulative distribution functions. A stream temperature regression model was also developed to assess potential changes in stream thermal regimes, which could cause shifts in composition of aquatic communities. Several flow regime variables, including those related to flow variability, duration of extreme events, and timing were mainly affected by changing climate. At the watershed scale, most indicators were relatively insensitive to changing climate and the magnitude of stream health decline was low. However, at the reach scale, there are many instances of high risk and large magnitude of declines in the stream health indicators. At the same time, several streams experienced changes in thermal class, mostly transitioning from cold-transitional and cool streams to warm streams. This research demonstrated the applicability of the stream health modeling process in performing a climate change impacts assessment.

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1. Introduction

Since 1951, the Earth's surface has warmed by 0.72 °C, while the last three decades were successively warmer than any ever recorded (IPCC, 2013). The Intergovernmental Panel on Climate Change (IPCC) concluded that it is extremely likely that anthropogenic activities, primarily greenhouse gas (GHG) emissions, caused more than half of these increases (IPCC, 2013). By the end of the 21st century, increases in global average surface temperatures projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations are projected to be between 0.3 and 4.8 °C depending on radiative forcing, although these increases will vary regionally (IPCC, 2013). As the atmosphere warms, its water holding capacity will increase and the hydrologic cycle will intensify, resulting in changes in frequency of precipitation extremes and increased evaporation and dry periods (Leibowitz et al., 2014; Piani et al., 2010; Praskievicz and Bartlein, 2014; Prudhomme et al., 2014). These changes in the hydrologic cycle have potentially serious implications for water resources and freshwater ecosystems. Hydrologic conditions such as floods and droughts have direct ecological effects (Lytle and Poff, 2004), while water temperature is a controlling factor on species distribution and community composition (Durance and Ormerod, 2007; DeWeber and Wagner, 2014). Some locations have already experienced shifts in aquatic community composition and structure toward selection of species that tolerate increased temperature and lower flows (Chessman, 2009). The IPCC (2014) has recognized that climate change is a significant threat to global biodiversity and ecosystem function.

Biological assessments are a commonly used tool to assess the health of freshwater ecosystems. Biological assessments measure

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* Corresponding author at: Department of Biosystems and Agricultural Engineering, Michigan State University, 524 S. Shaw Lane, Room 225, East Lansing, MI 48824, United States. Tel.: +1 517 432 7653; fax: +1 517 432 2892.
E-mail address: pouyan@msu.edu (A.P. Nejadhashemi).

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an aquatic ecosystem's biological integrity and the effects of stressors on that ecosystem's biota (USEPA, 2011). Here, the biological integrity of an ecosystem is based on its ability to "support and maintain a balanced, integrated, and adaptive community of organisms with a species composition, diversity, and functional organization" that is similar to that region's natural habitat (Karr, 1987). Multimetric biological indices or biotic indicators are a commonly accepted method for measuring ecosystem health and response to stressors (Einheuser et al., 2012). They measure ecosystem quality by communicating severity and extent of impairment through establishing a gradient of biological condition (Karr and Yoder, 2004). For example, the fish Index of Biotic Integrity (IBI) consists of metrics that describe structure, composition, and functional organization of a fish community (Lyons et al., 1996). In addition to fish, macroinvertebrates are prominently used in biological assessments because they respond quickly to a multitude of stressors at local scales (Flinders et al., 2008; Herman and Nejadhashemi, 2015). Using several biotic indicators is beneficial because it provides a holistic assessment of ecosystem health (Clapcott et al., 2012).

Community-level biological assessment is critical in light of potential climate change (Woodward et al., 2010). Most studies linking climate change and aquatic ecosystems have focused on individual species and taxonomic groups rather than communities (Lawrence et al., 2010; Woodward et al., 2010) such as individual macroinvertebrates (Domisch et al., 2011) and salmonids (Rahel et al., 1996; McDaniels et al., 2010; Isaak et al., 2012). Meanwhile, there are concerns that existing biotic indices ignore the potential effects of a changing climate and may become obsolete (Woodward et al., 2010). However, studies in Europe (Leunda et al., 2009) and North America (Lawrence et al., 2010) determined that biotic indicators were robust in response to a changing climate, establishing their continued utility in biological assessment. In addition, Lawrence et al. (2010) demonstrated that higher taxonomic resolutions (order and family) rather than genus and species were useful for detecting climate change.

Climate change impacts assessments that focus on individual species responses are invaluable, but natural resources managers are often interested in the broader system view that biological assessments provide. At the same time, our knowledge of ecological conditions at large scales is limited by incomplete monitoring data (Wang et al., 2008; Einheuser et al., 2012). Therefore, the goal of this research is to focus on the impacts of climate change on broader ecosystems health. By developing biotic indicator models of fish and macroinvertebrates, we can establish a system-level outlook of potential changes in stream health.

2. Materials and methods

2.1. Study watersheds

Seven 8-digit hydrologic unit code (HUC-8) watersheds in Michigan, USA were the subjects of this study: the Au Sable (HUC 04070007), Boardman-Charlevoix (HUC 04060105), Cedar-Ford (HUC 04030109), Flint (04080204), Muskegon (04060102), Pere Marquette-White (04060101), and Raisin (04100002) (Fig. 1). The watersheds were selected based on their availability of fish and macroinvertebrate sampling data, and diversity of physiographic characteristics including land use, soils, and stream thermal classes.

Drainage areas of the watershed range 2639 km^2 for the Cedar-Ford to 7071 km^2 for the Muskegon. Land use characteristics of the watersheds vary, where the Au Sable, Boardman-Charlevoix, and Cedar-Ford primarily consist of forests and wetlands, while the Flint, Raisin, Muskegon, and Pere Marquette-White are a mix of agriculture, forests, urban areas, and wetlands. Soils range from well-drained sandy soils for the Au Sable, Boardman-Charlevoix, Muskegon, and Pere-Marquette White to more poorly drained soils in the Flint and Raisin watersheds.

The Au Sable River watershed surface geology consists of coarse-textured sands and gravels from glacial and ice-contact outwash (Zorn and Sendek, 2001). Over 90% of the watershed consists of sand, loamy-sand, or wet-sandy-organic (Zorn and Sendek, 2001). The sandy soils are poorly consolidated and susceptible to erosion. Soil and geologic conditions in the watershed cause high groundwater inflows and very stable streamflow (Zorn and Sendek, 2001). Almost 90% of the stream length in the watershed is composed of headwater streams (Strahler stream order 1–3), while the remaining is order 4–6, where order 6 makes up 6% of total watershed stream length (152 km).

The Boardman-Charlevoix watershed consists of similar surficial geology and soils, where glacial till and outwash dominate. Soils are primarily dry and sandy of the Kalkaska, Grayling, and Rubicon series (Kalish and Tonello, 2014). However, the fruit-growing areas of the watershed are characterized by poorly drained organic soils such as Tawas and Carbondale (Kalish and Tonello, 2014). Flows in the Boardman watershed and tributaries are very stable due to the geology and soils. Hydrologic conditions in the Boardman-Charlevoix are similar to the Au Sable, given their similar geology, soils, and geographic proximity. Over 90% of the watershed is composed of headwater streams, while 5 is the highest stream order present.

The Cedar-Ford watershed surficial geology is primarily made of medium-textured glacial till. Alfisols and histosols are the dominant soil types, alternating between well drained and poorly drained conditions. Slopes in the watershed are moderate, averaging between 1 and 7%. Streamflow in the watershed is moderately stable. The Cedar-Ford watershed has the smallest stream orders of the study watersheds: 86% of the stream length is order 1–3, with the remaining 14% being 4th order streams.

The Flint River watershed geology and soils vary widely from the headwaters to the outlet. The headwaters are generally comprised of rolling hills with sandy loam glacial moraines, while the downstream reaches and main branch of the Flint River flatten out into a glacial lake plain with poorly drained clay and sandy soils (Leonardi and Gruhn, 2001). Alterations in the Flint River watershed (e.g. urbanization and agricultural expansion) have led to unstable daily flows that are highly responsive to storms and snowmelt. The Flint River is the only river in the study watersheds to reach order 7 (for 8 km of its length). Almost 90% of the total watershed stream length is comprised of headwater streams, while the remaining streams are generally of order 4–5.

The Muskegon River watershed is dominated by glacial landforms that support constant groundwater inputs (O'Neal, 1997). Soils in the watershed are primarily classified as moderately and highly permeable. Glacial aquifers composed of lacustrine sand, till, and outwash and glaciofluvial deposits underly the entire watershed (O'Neal, 1997). Daily streamflow for the Muskegon River and its tributaries are moderately stable with high levels of groundwater input (O'Neal, 1997). Stream orders in the Muskegon are 90% headwaters, and 10% mid-reaches. The Muskegon River itself is order 6 for 171 stream km.

The Pere Marquette-White watershed geology is primarily glacial drift, with both high moraines and low outwash plains (Balke et al., 2011). Overlying soils are sandy with moderate to excessive drainage. Some hydric soils are present (mucky sand and muck) and form wetland complexes in the headwaters of the watershed (Balke et al., 2011). Topography in the watershed is generally flat. Given the surface geology and soils, streams in the Pere Marquette-White watershed are generally groundwater fed and moderately stable (Balke et al., 2011). Stream orders in the Pere Marquette-White are 87% order 1–3 and 13% order 4–6, where over half of the total stream miles are 1st order streams.

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