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Research Paper

Predicting stream vulnerability to urbanization stress with Bayesian network models

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ABSTRACT

As human development and urbanization expand across the landscape, increasing numbers of streams are threatened with impairment from disturbance and stresses associated with land use changes. In this investigation, a Bayesian Network (BN) with an expert-informed model structure was developed to predict stream vulnerability to urbanization across a range of biophysical conditions. Primary factors affecting vulnerability were stream buffers, colonization connectivity, agriculture, watershed area, and sand/gravel aquifers. On a scale from 0 to 100 (lowest to highest probability), BN model vulnerability scores ranged from a minimum of 20 to a maximum of 87.5 across the 23,554 stream catchments in our statewide study area. Catchment vulnerability scores were linked with predictions of land development suitability from a second BN model in order to map the locations of streams at risk of impairment from projected future urbanization in two large watersheds in Maine, USA. Our BN synthesis identified 5% of the streams that are at risk based on two assessment criteria: (1) their catchments have projected future impervious cover (IC) levels greater than 6% and (2) the stream catchments have predicted vulnerability scores in the highest quartile of the BN model probability distribution. These at-risk streams represent priority targets for proactive monitoring, management, and conservation efforts to avoid future degradation and expensive restoration costs. This study laid the conceptual groundwork for using BN spatial models to identify streams that are not only vulnerable to urbanization, but are also located in catchments classified with a high probability of development suitability and future urbanization.

1. Introduction

An undeveloped forested watershed can tolerate only a limited amount of urbanization and human development activity before symptoms of stress and degradation begin to appear in downstream aquatic ecosystems. However, the response of streams to anthropogenic land use changes can vary as a function of watershed biophysical conditions that influence resistance or resilience properties of the coupled catchment and stream system (Alberti and Marzluff 2004; McCluney et al., 2014; Utz et al., 2016). In general, one would expect the streams at highest risk of impairment from development to be those with watershed characteristics that confer low resistance or high vulnerability to changing land use conditions or urbanization. Here, *resistance* refers to the ability of an ecosystem to resist change and to maintain structure and function despite increased exposure to stressors (Pearsons and Li 1992; Vieira, Clements, Guevara, & Jacobs, 2004). Conversely, *vulnerability* describes the sensitivity of a system to a stress and the degree to which the system will experience harm due to exposure to a stressor or perturbation (Besaw et al., 2009; Turner et al., 2003). *Resilience* describes the ability of a system to recover from disturbance or stress.

Under authority of the federal Clean Water Act (CWA) and state water quality standards, the U.S. Environmental Protection Agency (US EPA) and state regulatory agencies endeavor to sustain healthy aquatic resources and to restore the chemical, physical, and biological integrity of waters that have been impaired by urbanization, non-point pollution, or other stressors. In Maine, the Department of Environmental Protection (Maine DEP) monitors the health of streams and determines

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if they attain water quality standards and criteria associated with four state-defined statutory classes (Courtemanch, Davies, & Laverty, 1989; Danielson et al., 2012; Davies, Drummond, Courtemanch, Tsomides, & Danielson, 2016). If a stream does not attain water quality standards or criteria associated with its designated class, then it may be listed as impaired in the CWA 303(d) inventory of impaired waters (Maine DEP, 2012a). Unfortunately, the economic cost of restoring impaired streams can be substantial − as one example, ongoing restoration of the impaired Long Creek ecosystem in Portland, Maine is projected to cost $14 million (FB Environmental Associates 2009). With 2300 miles of streams and rivers currently classified in 303(d) impaired status by US EPA, Maine faces a daunting and expensive mitigation and restoration challenge. Given this set of circumstances, we argue that a proactive policy focused on avoiding stream impairment is a more cost-effective and sustainable approach to resource management than a reactive strategy that necessitates large expenditures to restore streams and rivers after they become degraded. The question then becomes: how can we identify streams that are at risk of future impairment, so that they can be protected by appropriate smart growth strategies or watershed conservation actions?

Any answer to that question will necessarily involve a focus on impervious cover. As urbanization expands in the landscape, stream quality generally decreases when impervious cover (IC) – any surface such as a road, parking lot, or roof that impedes water infiltration into the soil – approaches or exceeds 10% of the area in a watershed (Schueler, Fraley-McNeal, & Cappiella, 2009). In fact, Maine watersheds with IC values above 6% have been shown to exhibit marked declines in aquatic insect diversity that are indicative of ecological degradation (Morse, Huryn, & Cronan, 2003). More recently, Danielson et al. (2016) reported that there is a rapid loss of sensitive species between 1 and 3% IC and the risk of not attaining Class AA and A biological criteria is high after 3% IC. There is an additional loss of sensitive species between 3 and 6% IC and the risk of not attaining Class B biological criteria is high after 6%. Although it is widely accepted that stream integrity declines when urban area or IC increases beyond a certain threshold, the rate of degradation and the IC threshold can be variable. This implies that differences in watershed or environmental characteristics may mitigate or exacerbate patterns of stream vulnerability to urbanization.

Unfortunately, few studies have examined explicit ways in which watershed biophysical factors influence stream sensitivity to development and land use changes. There is, however, an extensive literature focused on landscape attributes that contribute to stream impairment and the degradation of downstream water quality. Investigators in several studies have demonstrated that agricultural cover in a watershed contributes to declines in stream water quality and a loss of biotic integrity (Allan, Erickson, & Fay, 1997; Carpenter et al., 1998). In Wisconsin watersheds, urbanization consistently contributed to degraded streams, whereas the influence of agriculture on streams was more variable (Wang, Lyons, & Kanehl., 2001). Strayer et al. (2003) found that cultivated and urban lands in the Mid-Atlantic region were associated with symptoms of stream degradation (e.g., high N, low fish species richness, high proportion of exotic fish, and low macroinvertebrate species richness), but wetlands, forests, and pastures were correlated with desirable stream quality traits. A number of models have been created using landscape variables to predict physical, biological, or chemical conditions in streams. In one example, investigators used a geologic classification system based on acid neutralizing capacity (ANC) and other landscape variables to predict the locations of acid-sensitive and acid-impacted streams in the southern Appalachian Mountains (Sullivan, Webb, Snyder, Herlihy, & Cosby, 2007). A model developed by Carlisle et al. (2009) used riparian land cover, road-stream intersections, elevation, soil permeability, depth-to-water table, and percent agricultural land cover to predict biological condition in streams in the Eastern U.S. Esselman et al. (2011) calculated a cumulative disturbance index for each U.S. watershed using a model relating fish IBI (index of biotic integrity) to anthropogenic disturbance variables such as percent urban or agricultural area in the watershed, population density, road density, dams, and mines. In a similar study, Bedoya et al. (2011) developed a model to predict IBI scores for streams in Ohio, and identified hay/pasture lands, deciduous forest, low intensity development, open urban land, woody wetlands, and deciduous forest within a stream buffer zone as key model variables. Taken as a whole, previous studies have indicated that impacts from anthropogenic stressors are widely manifested either directly through urban and agricultural runoff or indirectly through the removal of forests and wetlands.

Despite the growing number of analyses of correlations between landscape features and water quality, there has been only a limited effort to predict the relationships between modeled future land use conditions and stream water quality. The few studies that have examined future conditions have tended to use buildout analyses (Conway and Lathrop, 2005), which consider the implications of full construction in accordance with current zoning. In one novel exception to the buildout approach, Van Sickle et al. (2004) applied four alternative land use futures scenarios to predict the biological condition of streams in the Willamette River Basin, Oregon for the year 2050. They reported that agricultural lands and development within a 120 m stream buffer were two primary determinants of stream condition. Although alternative futures models have not yet been widely applied to stream quality issues, such models provide a way to develop and to target preventive water quality protection strategies that are likely to be less expensive and disruptive than reactive strategies initiated after water quality impairment sets in.

In this research, we built on these previous efforts by integrating a model of landscape-water quality interactions with a second model of future land use development. We used a Bayesian Network (BN) to explore the causal web of interacting factors that account for stream vulnerability to urbanization stressors. Bayesian Networks (BNs) provide a novel model framework for addressing ecological research problems (Chen and Pollino, 2012; Marcot, Holthausen, Raphael, Rowland, & Wisdom, 2001; Uusitalo, 2007), and have been used in recent years to assess population viability for at-risk fish and wildlife (Marcot et al., 2001), for land suitability analyses (Chow and Sadler 2010; Meyer, Johnson, Lilieholm, & Cronan, 2014), for adaptive management decision-making (Nyberg, Marcot, & Sulyma, 2006), for water quality predictions (Reckhow 1999), and for examining relationships linking urban development to physical, chemical, and biological conditions in a stream (Kashuba et al., 2012). These prior studies have identified several potential advantages of Bayesian modeling, including the ability to incorporate expert knowledge into a deductive framework for making predictions. For our purposes, the BN modeling approach provided a tool for combining expert knowledge and GIS spatial information to predict the statewide distribution of streams that have an elevated risk of degradation from watershed urbanization.

This investigation focused on identifying resistance and resilience factors that influence the vulnerability of streams and watersheds to urbanization, and integrating that knowledge into a predictive BN modeling framework for application to the sustainable management of aquatic resources. The major objectives of this study were to: (1) develop a spatially-explicit Bayesian Network (BN) model based on environmental data, stream biotic metrics, and expert knowledge in order to identify landscape characteristics that contribute to an increase or decrease in stream vulnerability to urbanization; (2) predict the potential vulnerability of individual streams in the Maine landscape to future urbanization stress; and (3) assess the spatial distribution of at-risk or vulnerable streams in relation to areas that are most likely to experience future development and urbanization based on alternative futures modeling projections. Our results demonstrate how BN models can provide a conceptual framework and a valuable predictive tool for resource managers and planners to use in (1) envisioning alternative future scenarios of watershed development; (2) prioritizing specific