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Research article

Assessing the impacts of land use on downstream water quality using a hydrologically sensitive area concept

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ABSTRACT

Understanding the relationship between land use and water quality is essential to improve water quality through carefully managing landscape change. This study applies a linear mixed model at both watershed and hydrologically sensitive areas (HSAs) scales to assess such a relationship in 28 northcentral New Jersey watersheds located in a rapidly urbanizing region in the United States. Two models differ in terms of the geographic scope used to derive land use matrices that quantify land use conditions. The land use matrices at the watershed and HSAs scales represent the land use conditions in these watersheds and their HSAs, respectively. HSAs are the hydrological "hotspots" in a watershed that are prone to runoff generation during storm events. HSAs are derived using a soil topographic index (STI) that predicts hydrological sensitivity of a landscape based on a variable source area hydrology concept. The water quality indicators in these models are total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) concentrations in streams observed at the watershed outlets. The modeling results suggest that presence of low density urban land, agricultural land and wetlands elevate while forest decreases TN, TP and/or TSS concentrations in streams. The watershed scale model tends to emphasize the role of agricultural lands in water quality degradation while the HSA scale model highlights the role of forest in water quality improvement. This study supports the hypothesis that even though HSAs are relatively smaller area compared to watershed, still the land uses within HSAs have similar impacts on downstream water quality as the land uses in entire watersheds, since both models have negligible differences in model evaluation parameters. Inclusion of HSAs brings an interesting perspective to understand the dynamic relationships between land use and water quality.

1. Introduction

Rapid urbanization has significantly transformed the landscape in the U.S. during last four decades (USDA, 2015). New Jersey being the most densely populated state in the U.S. represents such a typical landscape transformation. From 1986 to 2012, approximately 29 percent increase in urban lands was observed in New Jersey, accompanied by 26.7 percent decrease in agricultural lands, 6.7 percent decrease in forest, and 5.4 percent loss in wetlands (Lathrop et al., 2016).

Urbanization increases impervious surface area and alters magnitude, volume, frequency, and timing of high streamflow events (Shuster et al., 2005; Walsh et al., 2005), which causes streambank erosion, modifies channel morphology, transports nutrients, metals, pharmaceuticals, and toxic substances to streams (Fitzpatrick et al., 2005; Hatt et al., 2004; and Kolpin et al., 2002), and directly or indirectly changes hydrological, biological, and chemical processes of an aquatic ecosystem (Li and Zhang, 2011; Li et al., 2009; Yu et al., 2013). Water quality degradation has prompted an increasing interest in better understanding how land uses in a landscape affect downstream water quality (Huang et al., 2013; Li et al., 2009; Pratt and Chang, 2012; Wan et al., 2014; Wilson and Weng, 2010). There are numerous researches that have attempted to better understand the effects of land use on water quality (Giri et al., 2012, 2016; Huang et al., 2013; Li et al., 2009; Nejadhashemi et al., 2011; Wilson and Weng, 2010). Two most commonly used approaches are biophysical watershed modeling and statistical modeling. The biophysical watershed modeling

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involves extensive input data, model calibration, and in-depth modeling knowledge and has become a specialized expertise in water resource management. Statistical modeling offers a simpler alternative to biophysical watershed modeling by directly linking land use conditions and water quality that can be applied efficiently to a large region. Most statistical modeling studies use non-spatial land use matrices such as percentage of urban land and impervious surface cover in a watershed to determine the effects of land use on downstream water quality (e.g. Comelo et al., 1996; Johnson et al., 1997). Such non-spatial landscape indicators assume that each part of landscape has equal potential to affect stream water quality, which is overly simplistic and might misunderstand the relationship between land use and water quality (Williams et al., 2005).

Two types of progress have been made to overcome the limitation of such simplistic non-spatial landscape representation. First, an inverse distance weighted statistical approach was developed to assess the relationship between land use and water quality. This approach assigned more weights to land uses closer to a stream than land uses further away from the stream when evaluating the impacts of land use on stream water quality (Kennen et al., 2008; Peterson et al., 2010). Second, critical areas such as riparian zones of streams were considered to have the most significant impacts on stream water quality (NRC, 2002). The land uses within the riparian zones instead of whole watershed were consequently used to assess the impacts of land use on stream water quality (Baker et al., 2006; Paringit and Nadaoka, 2003). Although the riparian zone approach is interesting, it has some drawbacks (Qiu, 2009). First, there is no uniform way of defining the width of riparian zones. Second, riparian zone is not a surrogate measure of hydrological sensitivity considering spatially varying hydrological connectivity in landscape.

We use a concept called hydrologically sensitive areas (HSAs) to improve the understanding of hydrological connectivity between terrestrial landscapes and aquatic stream. HSAs are the areas in a watershed having higher propensity to generate runoff. This is consistent with the variable source area (VSA) hydrology concept where the primary source of runoff is saturated areas in uplands, whose scale varies depending on storm intensity (Qiu et al., 2014; Walter et al., 2000). These smaller saturated areas in a watershed primarily generate and transport pollutants to streams and influence stream hydrographs (Hewlett, 1982).

Although some studies (e.g. Easton et al., 2008; Heathwaite et al., 2005; Qiu, 2009; Walter et al., 2000, 2009) have used VSA hydrology to identify HSAs and target best management practices (BMPs) to control nonpoint source pollution, however, they were conducted on agricultural field or small watershed scale with implicit assumption that BMPs within HSAs would be more effective in improving water quality. No study has attempted to empirically test and validate whether the high-intensity land uses within HSAs such as agricultural and urban lands contribute more to water quality degradation across watersheds. The objectives of this study is to assess the impact of land use at both HSAs and watershed scale on water quality using a linear mixed model and to test the hypothesis that even though HSAs represent a small fraction of a watershed, the land uses within HSAs have the similar impacts on downstream water quality as the land uses in the watershed. Validation of such a hypothesis is a critical step to the development of efficient watershed management strategies for water quality improvement. For example, watershed manager can strategically target HSAs for implementing BMPs to enhance their effectiveness and cost-effectiveness in improving water quality if the hypothesis is deemed to be true.

2. Materials and methods

2.1. Study area

This study was conducted in 28 watersheds located in the northcentral New Jersey including Essex, Hunterdon, Mercer, Middlesex, Monmouth, Morris, Somerset, Sussex, Union, Passaic, Burlington, and Ocean Counties (Fig. 1). All 28 watersheds were located in three physiographic regions including Valley and Ridge, Highlands, and Piedmonts where VSA hydrology is considered to be a dominant hydrological process for runoff generation (Qiu, 2009; Walter et al., 2002). There were 68 watersheds with the long-term water quality monitoring stations in the region, but we only selected these 28 watersheds having no water transfer and located entirely in New Jersey.

The watersheds were delineated using the Streamstats, a web-based watershed delineation tool developed and maintained by the U.S. Geological Survey. Latitude and longitude of each water quality monitoring station were submitted through the Streamstats interface to obtain the watershed boundary. An example of delineated watershed using the Streamstats is presented in Fig. 2.

These watersheds vary in size from 24 square kilometers (km^2) to 2062 km^2. These watersheds had experienced varying degrees of urbanization. The primary urbanization form is the expansion of low density residential areas, accompanied by losses in agricultural land, forest, and wetlands (Lathrop et al., 2016). Such changes in land uses have altered watershed hydrology as well as the physical, chemical, and biological condition of streams in New Jersey (Kennen et al., 2008, 2010).

2.2. Soil topographic index

Soil topographic index (STI) is an indicator of hydrological sensitivity of a landscape and is calculated using following equation (Giri et al., 2017; Buchanan et al., 2014; Qiu, 2009; Walter et al., 2002):

$$STI = ln\left(\frac{\alpha}{T\ \tan(\beta)}\right) \tag{1}$$

where α is the upslope contributing area per unit contour length (m), β is the local surface slope (mm^{-1}), T is a soil transmissivity (m^2/day) computed as the product of the saturated hydraulic conductivity (m/day) and the depth to a restrictive layer (m). STI indicates the likelihood of a point in a watershed to generate runoff and is used to identify spatial distribution of runoff contributing areas in watersheds (Qiu, 2009). Wetness index, $ln\left(\frac{\alpha}{tan(\beta)}\right)$, was the most common form of topographic index (Beven and Kirkby, 1979). STI extends this topographically based wetness index by considering soil water storage capacity above a restrictive layer and is more applicable to the hydrological process in the Northeast in the U.S. (Buchanan et al., 2014; Qiu, 2009; Walter et al., 2002).

2.2.1. Soil transmissivity

Soil transmissivity was based on soil saturated hydraulic conductivity and soil depth (Buchanan et al., 2014) of topsoil layers in the soil survey geographic (SSURGO) database downloaded from the U.S. Department of Agriculture (USDA) Geospatial Gateway. The information on saturated hydraulic conductivity and the soil depth in the SSURGO database was extracted using a soil data viewer developed by USDA Natural Resources Conservation Service. This saturated hydraulic conductivity for calculating T in Equation (1) is the geometric mean of the saturated hydraulic conductivity of all soil layers above a restrictive layer (Qiu, 2009). A correction factor