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Research article

An integrated modeling approach for estimating hydrologic responses to future urbanization and climate changes in a mixed-use midwestern watershed

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ABSTRACT

Future urban development and climatic changes are likely to affect hydrologic regimes in many watersheds. Quantifying potential water regime changes caused by these stressors is therefore crucial for enabling decision makers to develop viable environmental management strategies. This study presents an approach that integrates mid-21st century impervious surface growth estimates derived from the Imperviousness Change Analysis Tool with downscaled climate model projections and a hydrologic model Soil and Water Assessment Tool to characterize potential water regime changes in a mixed-use watershed in central Missouri, USA. Results for the climate change only scenario showed annual streamflow and runoff decreases (−10.7% and −9.2%) and evapotranspiration increases (+6.8%), while results from the urbanization only scenario showed streamflow and runoff increases (+3.8% and +9.3%) and evapotranspiration decreases (−2.4%). Results for the combined impacts scenario suggested that climatic changes could have a larger impact than urbanization on annual streamflow, (overall decrease of −6.1%), and could largely negate surface runoff increases caused by urbanization. For the same scenario, climatic changes exerted a stronger influence on annual evapotranspiration than urbanization (+3.9%). Seasonal results indicated that the relative influences of urbanization and climatic changes vary seasonally. Climatic changes most greatly influenced streamflow and runoff during winter and summer, and evapotranspiration during summer. During some seasons the directional change for hydrologic processes matched for both stressors. This work presented a practicable approach for investigating the relative influences of mid-21st century urbanization and climatic changes on the hydrology of a representative mixed-use watershed, adding to a limited body of research on this topic. This was done using a transferrable approach that can be adapted for watersheds in other regions.

1. Introduction

Land-use and climatic changes are two of the most significant phenomena impacting water regimes globally (Brown et al., 2014; Chung et al., 2011). In terms of land-use change, urban development is second only to agriculture in terms of impairing stream ecosystems (Paul and Meyer, 2001). In many areas throughout the world, rapid spates of urban development have also been accompanied by the buildup of impervious surface (IS) cover, which alters the hydrologic characteristics of watershed landscapes (Kumar et al., 2013; Schueler et al., 2009). The development of these impervious surfaces within watersheds affects the overall hydrologic balance and impacts individual water balance components, often through increased runoff, reduced evapotranspiration and decreased infiltration (Arnold and Gibbons, 1996; Paul and Meyer, 2001; Redfern et al., 2016; Chen et al., 2017). Relatedly, it has been demonstrated that future urbanization and impervious surface expansion will likely lead to changes in the amount and timing of streamflow, surface runoff and baseflow (Kumar et al., 2013; Sunde et al., 2016; Wu et al., 2015), and result in evapotranspiration (ET) reductions (Kim et al., 2011; Sunde et al., 2016). However, the complexity of the relationship between urban development and water balance processes warrants further investigation into these potential changes, as hydrologic responses to imperviousness differ among various watersheds (Beck et al., 2016; Redfern et al., 2016). While some past research has attempted to help address such issues by linking urban growth projections with hydrologic models in

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order to estimate the potential impacts of future urbanization on watershed hydrologic processes (Choi and Deal, 2008; Kumar et al., 2013; Lin et al., 2008; Sunde et al., 2016; Wu et al., 2015), developing a clearer understanding of how hydrologic processes respond to urban development in its various forms remains an important management issue.

Climatic changes, such as increased temperatures and altered precipitation regimes, can also impact watershed hydrologic processes (Arnell and Gosling, 2013; Jiménez-Cisneros et al., 2014). For example, increasingly frequent extreme precipitation events (Pryor et al., 2014; Walsh et al., 2014) during the past century in the Midwestern United States have already contributed to increased surface runoff and streamflow across much of the region (Romero-Lankao et al., 2014; Jiménez-Cisneros et al., 2014; Georgakakos et al., 2014). Climate projections also suggest that both the frequency and magnitude of such events could continually increase over coming decades (Sun et al., 2015; Walsh et al., 2014). Projected changes to the precipitation regime vary directionally by season. In Midwestern states such as Missouri, 21st century climate model projections suggest sizeable precipitation increases during the winter and spring, minor increases during the fall, and decreases during summer (Sun et al., 2015). Temperatures and heat wave occurrences have already increased across the region (Pryor et al., 2014), and climate projections indicate that these will continually increase during the rest of this century (Romero-Lankao et al., 2014; Walsh et al., 2014; Sun et al., 2015). These temperature increases are likely to contribute to increased ET in many areas (Jiménez-Cisneros et al., 2014) and are expected to lead to soil moisture decreases across most of the Midwestern region, most notably during summer (Walsh et al., 2014). Understanding hydrologic responses to these climatic changes is important as these can have implications for water supplies, nutrient loading to receiving bodies, and other critical management issues. Some of these potential changes have been investigated in past studies, where climate model projections have been integrated with hydrologic models to estimate potential climate change effects on water regimes (Cherkauer and Sinha, 2010; Chien et al., 2013; Dams et al., 2015; Ficklin et al., 2009; Jin and Sridhar, 2012; Joh et al., 2011; Mohammed et al., 2015; Ouyang et al., 2015; Sheshukov et al., 2011; Vo et al., 2016; Xu et al., 2013).

The hydrologic responses to climatic changes observed in previous studies were variable, owing largely to differences in the characteristics of the watersheds being analyzed, yet it has been consistently demonstrated that hydrologic processes such as surface runoff, streamflow, baseflow, and ET are likely to be impacted by future climatic changes in most areas (Cherkauer and Sinha, 2010; Dams et al., 2015; Ficklin et al., 2009; Joh et al., 2011; Ouyang et al., 2015; Sunde et al., 2017; Wang et al., 2017; Xu et al., 2013). However, since most areas have experienced land-use changes (e.g. urbanization, deforestation) and climatic changes concurrently, it is often difficult to attribute observed water regime changes to climate change or land cover change alone (Bierwagen et al., 2010; Georgakakos et al., 2014). It has been shown that the relative influence of the two stressors can vary, and that water regime processes respond differently depending on watershed characteristics (Cuo et al., 2011; El-Khoury et al., 2015; Fan and Shibata, 2015; Franczyk and Chang, 2009; Mishra et al., 2010; Neupane and Kumar, 2015; Pervez and Henebry, 2015; Qi et al., 2009; Rahman et al., 2015; Viger et al., 2011). To address this issue, integrated modeling approaches using land-cover change models, climate projections, and hydrologic models have been incorporated into some studies to investigate both the individual and combined hydrologic impacts of climatic and land-use changes. In some instances, studies have indicated that climatic changes can more severely impact water regimes than urbanization and/or land-use changes (Cuo et al., 2011; Fan and Shibata, 2015; Qi et al., 2009; Rahman et al., 2015; Wang et al., 2014; Wilson and Weng, 2011). However, for other areas, it has been demonstrated that land-cover changes could have greater impacts than climatic changes on streamflow processes (Mishra et al., 2010). In addition, the impacts of climatic and land-cover changes on hydrologic processes can be compounded by one another in some instances (El-Khoury et al., 2015; Franczyk and Chang, 2009; Neupane and Kumar, 2015) and offset by each other in other cases (Viger et al., 2011).

The previously discussed studies have contributed to a growing body of research investigating the impacts of two of the most significant stressors affecting hydrologic regimes globally. However, uncertainty regarding how watersheds in various regions will respond to the combined effects of future climatic and land-cover changes necessitates continued integrated modeling to improve the understanding of their respective influences on hydrologic processes. In urbanizing watersheds, this can be achieved using modeling approaches that utilize fine-scale urban growth projections, downscaled climate projections, and process-based hydrologic models to develop information with application potential for natural resource managers.

Given the preceding background and concerns, the overarching objective of this study was to use an integrated modeling approach to estimate the potential impacts of urbanization and climatic changes in a mixed-use watershed in the Midwestern United States. This approach involved simulating fine-scale future impervious surface growth for the study watershed using a cellular automata based urban growth model, calibrating and validating a process-based hydrologic model for the study watershed, and using downscaled global climate model (GCM) output with the projected impervious surface cover to force a hydrologic model to estimate the relative and combined effects of these stressors on streamflow processes for the study watershed. Specifically, these objectives were achieved by: 1) calibrating and executing the Imperviousness Change Analysis Tool (I-CAT) to simulate pixel level impervious surface cover for the Columbia, Missouri area, 2) conducting sensitivity analysis and parameterization of the Soil and Water Assessment Tool (SWAT) for Hinkson Creek Watershed and 3) using impervious cover derived from I-CAT along with downscaled GCM output from a stochastic weather generator to force SWAT and generate hydrologic estimates.

2. Methods

2.1. Study area

Located in the Midwestern US in central Missouri, Hinkson Creek Watershed (HCW) comprises an area of approximately 231 km^2 (Fig. 1). Elevations in HCW range from 170 to 290 m (Gesch et al., 2002), and land cover is approximately equal parts urban developed area, forest area, and agricultural (cropland/pasture) lands (Sunde et al., 2016). Karst features, bluffs, and loess-covered uplands are found throughout the central and southeastern portions of HCW, whereas the northwestern areas of the watershed are largely comprised of thin loess soils underlain by glacial till and claypans (Nigh and Schroeder, 2002). Based on its land-cover and economic characteristics, HCW is an emblematic contemporary mixed-use, urbanizing watershed (Hubbart and Zell, 2013). HCW encompasses approximately 60% of Columbia, Missouri, a city which has had large population increases and associated impervious surface development over recent decades (Sunde et al., 2016). From 2000 to 2015 the population of the city increased by over 41%, from approximately 84,000 to over 119,000 (US Census Bureau, 2015). Additionally, while impervious surface area in the watershed increased by just 12.7% from 1980 to 1990, recent urbanization has occurred more rapidly, with increases of 24.1% (1990–2000) and 32.5% (2000–2011) during the following decades (Zhou et al., 2012; Xian et al., 2011). After placement on the impaired waters list under the guidelines of the Clean Water Act in 1998, Hinkson Creek (HC) has been the subject of numerous studies. In some of these studies, researchers have characterized the local impacts of recent urbanization on hydrologic processes, nutrient and sediment yields, and aquatic biota in HCW (Hubbart and Zell, 2013; Kellner and Hubbart, 2016; Nichols et al., 2016; Zeiger and Hubbart, 2016a; b).