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Forecasting streamflow response to increased imperviousness in an urbanizing Midwestern watershed using a coupled modeling approach

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ABSTRACT

Increased impervious surface (IS) cover is often the primary disturbance contributing to altered hydrology in urbanizing watersheds, affecting various components of the hydrologic balance. To improve the understanding of how future urban development will influence watershed streamflow characteristics, and to develop growth strategies that preserve water resources, it is necessary to combine detailed estimates of future IS cover with hydrologic models. A coupled modeling approach is presented to help address this problem. Pixel-based percentage IS cover for the period 2011–2031 was derived using the Imperviousness Change Analysis Tool (I-CAT) for three urban growth scenarios and coupled with the Soil Water Assessment Tool (SWAT) to simulate the potential hydrologic impacts of future urbanization in Hinkson Creek watershed, located in the Midwestern U.S. state of Missouri. Increases to average annual streamflow (+12.81% to +19.74%), increases to average annual surface runoff (+14.32% to +16.77%), reductions to evapotranspiration (−8.68% to −13.37%), and slight increases to baseflow were observed for the three growth scenarios. The approach used here created a range of possible future conditions for the study watershed and presented a framework that allows planners to couple realistic IS cover estimates with hydrologic models. Additionally, this study emphasized that a controlled, more environmentally conscious growth pattern does not necessarily produce less pronounced hydrologic impacts for the study watershed compared to an uncontrolled growth pattern, underscoring the importance of considering neighboring watersheds when analyzing the hydrologic impacts of urban development for an area.

1. Introduction

The build-up of impervious surfaces resulting from urban and residential development is often a primary disturbance altering the hydrology of watersheds (Paul & Meyer, 2001). In urbanizing watersheds, increased imperviousness can affect the dynamics of surface runoff, evapotranspiration, the infiltration of water into the soil profile, and groundwater recharge, thereby altering the timing and volume of streamflow and affecting the overall hydrologic balance (Arnold & Gibbons, 1996; Paul & Meyer, 2001). Additionally, runoff from impervious surfaces (e.g. rooftops, roads, and parking lots) expedites the flow of water into stream channels, transporting urban pollutants, increasing peak discharge volume, and intensifying flood risk (Arnold & Gibbons, 1996; Kim, Ko, Jeong, & Yoon, 2007). An improved understanding of how future urban development will influence streamflow characteristics in urbanizing watersheds is crucial for developing urban growth strategies that minimize the hydrological impacts of development and preserve water resources.

1.1. Background: integrated modeling

While the independent use of urban growth or hydrological

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models is relatively common, studies focused on the integration of these two types of models to characterize the effects of urbanization on watershed hydrology are far less common (Choi & Deal, 2008). Wu, Bolte, et al. (2015) and Wu, Zhan, et al. (2015) coupled future urban growth estimates for the Heihe River basin in Northwest China with a hydrologic model and found that streamflow could increase by over 9% by the year 2050. A study in the Willamette Valley in Oregon used an agent-based landscape change model to evaluate urban development impacts on various streamflow metrics (Wu et al., 2015). Significant flow regime changes were projected for the three basins in the study. Kumar, Arya, and Vojinovic (2013) used a binary cellular automata (CA) based urban growth model, along with the Natural Resources Conservation Service (NRCS) curve number method, to estimate the future impacts of urbanization on surface runoff for a watershed in India and found that expected urban growth of about 63% could lead to an 11% increase in peak stream discharge. In another study, an integrated CA-Markov model was coupled with the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) to estimate the impacts of urban growth on runoff and flood volumes in the Qinhuai River basin in China (Du et al., 2012). The Qinhuai River basin study was effective in identifying potential changes to peak discharge and flood volume, showing that an impervious ratio increase of 28% could result in a 6% average increase for peak flows, and an 8.5% average increase in simulated flood volume. Lin, Lin, Wang, and Hong (2008) used the SLEUTH and CLUE-s land use change models with the Generalized Watershed Loading Function (GWLF) model to examine the effects of urbanization on watershed hydrology in the Paochiao watershed in Taiwan. Their analysis indicated that future urbanization in the watershed could cause a 22% increase to surface runoff, and that baseflow could decrease by as much as 18%. Choi and Deal (2008) used the output from a CA urban growth model with the Hydrological Simulation Program—Fortran (HPSF) to forecast potential changes to surface runoff and streamflow in the Kishwaukee River basin, an urbanizing watershed near the western edge of Chicago. The study demonstrated that coupling the two models was useful for estimating the potential impacts of urban growth in the watershed, indicating a possible 38.5% increase in surface runoff and a 1.1% decrease in baseflow by the year 2051. Additionally, Arthur-Hartranft, Carlson, and Clarke (2003) developed a linear regression-based hydrologic module for SLEUTH using observed rainfall-runoff relationships and basin imperviousness to enable researchers to generate runoff estimates based on future land cover changes.

While all of the aforementioned studies were effective in linking urban growth forecasts with hydrologic models to assess the effects of land-use change in watersheds, they largely made use of binary urban growth classifications, rather than more detailed estimates of impervious surface area. Yet incorporating realistic impervious surface area estimates in such coupled modeling analyses is crucial for urban planners and watershed managers. This is due to the fact that a great deal of contemporary urban growth occurs in the form of low-density development, often referred to as urban sprawl, in which developed areas (e.g. pixels) contain only a low percentage of imperviousness (Zhou, He, Nigh, & Schulz, 2012), and because the percentage of a watershed that is comprised of impervious surface cover is a key indicator for assessing urban stream health (Arnold & Gibbons, 1996; Schueler, Fraley-McNeal, & Cappiella, 2009).

1.2. Objective

In the following study, a semi-distributed hydrologic model, the Soil Water Assessment Tool (SWAT; Arnold, Srinivasan, Muttiah, & Williams, 1998), was coupled with a CA urban growth model called the Imperviousness Change Analysis Tool (I-CAT; Sunde, He, Zhou, Hubbart, & Spicci, 2014), which is capable of producing detailed impervious surface cover estimates. The goal of this coupled modeling approach was to simulate the potential impacts of future urbanization on the hydrologic characteristics of a watershed located in the southern portion of the Midwestern United States, and to evaluate the hydrologic effects of possible future urban growth scenarios to determine if an uncontrolled growth pattern resulted in more pronounced hydrological impacts than a controlled growth pattern.

2. Methods

2.1. Study area

Hinkson Creek Watershed (HCW; Fig. 1) is an urbanizing watershed covering an area of approximately 231 km^2 in central Missouri, U.S.A., within the Lower Missouri-Moreau Basin. The northern and western portions of Hinkson Creek are situated in the Claypan Till Plains ecological subsection, on Grand Prairie-Prairie Plain land types, which are characterized by thin loess soil with underlying glacial till and claypans (Nigh & Schroeder, 2002). The central and eastern portions of the watershed lie inside the Outer Ozark Border ecological subsection, on Rock Bridge Oak Woodland/Karst Forest Hills land types. These areas consist of well-developed karst features, caves, losing streams, dissected valleys, bluffs, and loess-covered uplands (Nigh & Schroeder, 2002). According to U.S. Geological Survey (USGS) digital elevation models, elevations in HCW range from about 170 to 290 m (Gesch et al., 2002). A stream gauge site (USGS 06910230) located at Hinkson Creek recorded an average annual discharge rate of 1.80 m^3/s. Gauge records indicate that the months having the lowest amounts of average discharge are August (0.56 m^3/s) and November (0.73 m^3/s). The months exhibiting the highest rates of discharge are March (2.77 m^3/s), April (3.45 m^3/s), and May (3.01 m^3/s). The highest average seasonal discharge at Hinkson Creek occurs during spring (3.08 m^3/s), followed by the summer (1.59 m^3/s), winter (1.36 m^3/s), and fall (1.20 m^3/s) seasons. Based on records for the period 1994–2014 from the University of Missouri, Sanborn Field weather station, the average annual precipitation was 1015 mm and the mean annual temperature was 13.6 °C. The landscape of HCW is comprised of diverse land cover, with urbanized, forested, and agricultural lands being the most prevalent types. Given its current land-use, population growth, and commercial expansion characteristics, HCW typifies an urban watershed (Hubbart & Zell, 2013). Additionally, HCW has been the focus of various efforts to mitigate erosion and nonpoint source pollution, stemming largely from the fact that Hinkson Creek was classified as impaired in 1998 under the guidelines of the Clean Water Act (Hubbart, Holmes, & Bowman, 2010).

Recent population growth in HCW has occurred at a rapid pace. Approximately 59% of the city of Columbia is situated in HCW and, between the years 2000 and 2014, the city population increased by 36.9%, from about 84,000 to over 115,000 (US Census Bureau, 2013). The rapid influx of residents into the area has also been accompanied by large amounts of urban development (i.e. built-up impervious surface areas). From 1980 to 1990, the amount of impervious surface cover in HCW increased by just 12.7% (+1.74 km^2). However, the period of 1990–2000 saw an increase in impervious surface cover of about 24.1% (+3.71 km^2), with over twice as much area developed as the previous decade (Zhou et al., 2012). An unprecedented amount of urban development occurred in HCW from 2000 to 2011, with an estimated 32.5% (+6.21 km^2) increase in impervious surface area, much of which was comprised of low-density