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Research article

Urbanization impacts on surface runoff of the contiguous United States

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1. Introduction

Urbanization is one of the most important anthropogenic modifications of the global environment (Antrop, 2004; DeFries and Eshleman, 2004; Eshleman, 2004; Foley et al., 2005; Weng, 2002; Wu, 2014). Every urban region in the United States has expanded substantially in area in recent decades (USEPA, 2013). Urbanization presents humans with a dilemma (Foley et al., 2005). On one hand, urban development is essential because it provides convenience of infrastructure, goods and services needed by people, government, economic development, industry, and trade (Foley et al., 2005; Lowry, 1990); on the other hand, land surface modifications occur during the process of urbanization including vegetation reduction, soil compaction, and change from pervious surfaces to impervious surfaces such as roofs, roads, and parking lots (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Schueler, 1994). The consequences of these land surface modifications include but are not limited to: changes in water supply from altered hydrologic processes of infiltration, groundwater recharge, and runoff; water quality degradation from urban runoff and combined sewer overflows (CSOs); and changes in water demand (Burns et al., 2012; DeFries and Eshleman, 2004; Gitau et al., 2016; Passerat et al., 2011; Semadeni-Davies et al., 2008; Tong and Chen, 2002; Vietz et al., 2016).

In general, surface runoff and river discharge increase when natural vegetation, especially forests, decrease (Costa et al., 2003; Foley et al., 2005; Sahin and Hall, 1996). Impervious surfaces developed during urbanization contribute more surface runoff due to decreased infiltration (Arnold and Gibbons, 1996; Schueler, 1994; Schueler et al., 2009). Reduced infiltration leads to higher peak flows, even for short duration low intensity rainfall, and increases the risk of flooding (Bhaduri et al., 2001; Suriya and Mudgal, 2012). Urban runoff also carries non-point source pollutants, such as oil, grease, metals, and pesticides, into streams and rivers during rainfall events (Arnold and Gibbons, 1996; Blair et al., 2014; Schueler, 1994). Even if urban runoff is captured by a sewer system and can be conveyed to wastewater treatment plants, Combined Sewer Overflows (CSOs) in some highly urbanized areas continue to cause serious water pollution problems (Bhaduri et al., 2001; Passerat et al., 2011; Semadeni-Davies et al., 2008).

Computer-based hydrological models can save time and money because of their ability to perform temporal and spatial simulation of the effects of hydrologic processes and management activities on water quantity and water quality (Moriasi et al., 2007). The United States Department of Agriculture (USDA) Soil Conservation Services (SCS) Curve Number (CN) (Natural Resources Conservation Services (NRCS), 1986) approach is widely used in several hydrological models that are used to assess the impact of land use change on surface hydrology, including sophisticated models such as Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Srinivasan et al., 1998), as well as models adopting the philosophy of simplicity such as the Long-Term Hydrologic Impact Assessment (L-THIA) (Bhaduri et al., 2000; Harbor, 1994). Sophisticated models usually require more parameters to set up the model before simulation, which may create limitations due to lack of data or time (Bhaduri et al., 2001). L-THIA is an easy, quick, and user friendly

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tool, which only requires readily available data including hydrologic soil group (HSG), land use, and long-term rainfall data to assess surface runoff influenced by past, present, as well as future land management decisions for specific locations (Bhaduri et al., 2001; Grove et al., 2001; Tang et al., 2005). The L-THIA model has been successfully used in numerous studies to assess the impact of land use change on surface hydrology and water quality (e.g., Bhaduri et al., 2000; Choi, 2007; Davis et al., 2010; Grove et al., 2001; Gunn et al., 2012; Kim et al., 2002; Lim et al., 2006a, 2006b, 2010; Muthukrishnan et al., 2006; Pandey et al., 2000; Tang et al., 2005; Wilson and Weng, 2010). The L-THIA model has also been incorporated and integrated into Web-based and GIS-based decision support systems (Choi et al., 2003, 2005a, 2005b; Choi and Engel, 2003; Engel, 2001; Engel et al., 2003; Engel and Hunter, 2009; Pandey et al., 2000; Shi et al., 2004; Tang et al., 2004), as well as a low impact development model (Ahiablame et al., 2012a, 2012b, 2013; Engel and Ahiablame, 2011; Hunter et al., 2010; Liu et al., 2015a, 2015b, 2016a, 2016b; Martin et al., 2015; Wright et al., 2016).

Research evaluating urbanization impacts on surface runoff using L-THIA has focused primarily on watershed-scale analysis, and quantitative assessment of urbanization impacts on surface runoff at a national scale is limited. The release of National Land Cover Database (NLCD) 2011 edition datasets for 2001, 2006, and 2011 across the nation makes the assessment of urban land use change impacts on surface hydrology at the national level feasible (Homer et al., 2015). The NLCD extends land use/land cover coverage over larger areas at more frequent time intervals allowing large scale investigations to be conducted (DeFries and Eshleman, 2004). Explicit understanding of urbanization impacts on surface runoff will provide information for decision makers who need to balance trade-offs between the advantages and possible unintended consequences of urbanization. This study assessed urbanization impacts on surface runoff for 2001, 2006, and 2011 in the contiguous United States using the L-THIA Tabular Tool, a derivative of the L-THIA model. We first present the assessment of the normalized average annual runoff depth (NAARD) for 2001, 2006, and 2011 by contiguous U.S. counties and evaluate whether population change is a consistent indicator for urban development; then we present an assessment of NAARD for 2001, 2006 and 2011 by U.S. states; finally, we present the assessment of the national average annual runoff volume increase due to urbanization.

2. Methods and materials

2.1. L-THIA Tabular Tool

The L-THIA Tabular Tool, which shares the same philosophy as the original L-THIA model (Harbor, 1994), uses the SCS CN method (Natural Resources Conservation Services (NRCS), 1986) to calculate average annual runoff for land use and soil combinations based on long-term climate data for that area (Bhaduri et al., 2001). The runoff depth is estimated when rainfall exceeds initial abstraction based on (Natural Resources Conservation Services (NRCS), 1986):

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \text{ for } P > I_a = 0.2S$$
$$Q = 0 \text{ for } P \le I_a = 0.2S \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

$$I_a = 0.2S \tag{3}$$

where Q represents direct runoff depth in mm; P represents rainfall depth in mm; S represents potential maximum retention after runoff begins in mm; CN represents curve number; and I_a represents initial abstraction in mm.

The L-THIA Tabular Tool was developed using the Python programming language and is run as a toolbox in ArcGIS version 10.2.2. It is designed to expedite tabulating calculations over diverse geographical areas. An external component (a Java program) calculates daily runoff for all curve numbers using the equations above. The calculations are performed for each precipitation gauge in a region using daily rainfall and all curve numbers. The calculations are made for each year in the database (typically between 30 and 100 years). The user selects how many of the available years of annual runoff to average in order to create average annual runoff, and the same number of years is used from every gauge.

The ArcGIS implementation (a Python script tool) of L-THIA Tabular consists of three main components. The first component aims to generate a CN raster using land use and HSG combination. A six-digit combination raster layer including HSG (first digit), land use (second to third digits), and corresponding CN (fourth to sixth digits) was created for each pixel in the NLCD data, as shown in Table 1. The second component prepares the study area boundary for the runoff calculation. This operation determines which Thiessen polygons (Thiessen, 1911) representing rain gauges intersect the study area. The tool determines how many pixels of each of CN raster is within each Thiessen polygon. The third component is used to tabulate the selected years of average annual runoff, under antecedent moisture condition (AMC) II condition (normal antecedent soil moisture), using the CN raster information generated from the first component inside the study outline generated from the second component, as well as rainfall data. The tabulation consists of accumulating the area of each CN present in each precipitation polygon in the region, and fetching the appropriate runoff total for each CN from the web-based results of the runoff calculator, and averaging the requested number of years to obtain average annual runoff for each CN used in the study area. Runoff depth is converted to volume through multiplying by pixel area for each CN. The final outputs of L-THIA Tabular Tool include average annual runoff volume and depth within a given boundary. The units of the output average annual runoff volume and depth can be represented using both U.S. and metric units. The third component also computes non-point source pollution estimates using the runoff volume and the CN-land use pairs to choose the appropriate pollution coefficient (event mean concentration, EMC) if desired.

The study area is the contiguous United States, which includes 48 adjoining states and the District of Columbia (DC). The L-THIA Tabular Tool was set up to create analyses based on U.S. county boundaries. A total of 3109 counties were modeled. Calibration and validation would be challenging for a national analysis due to the scarcity of observed surface runoff data from county based urban areas. However, the SCS CN method is a well-known and widely used runoff estimation approach, and a substantial number of studies have reported its usefulness and credibility; for example, many L-THIA studies have validated the SCS CN method with little or no calibration (Ahiablame et al., 2013; Bhaduri et al., 2001; Grove et al., 2001; Kim et al., 2002; Liu et al., 2015b; You et al., 2012). Thus, this approach can be applied to assess surface runoff at a national scale.

2.2. Input data

In the L-THIA Tabular Tool, the basic input data include daily