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A need to revisit hydrologic responses to urbanization by incorporating the feedback on spatial rainfall patterns

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ABSTRACT

This study highlights the changes in the hydrologic responses to urbanization under idealized spatial heterogeneity in rainfall distribution. The study builds off recent assessments which show that urban areas modify the spatial rainfall pattern in its vicinity. Numerical experiments were conducted over an idealized watershed by prescribing different spatial patterns of rainfall and impervious coverage. Hydrologic responses were characterized by four metrics: flow distribution, daily variation, frequency of floods, and interannual runoff variability, as well as relative changes in flood magnitudes under different scenarios. Results indicate that hydrological response depends on both the spatial extent of urban coverage and the spatial patterns of rainfall. The most noticeable hydrologic variations and relative changes of flood magnitudes occur when the watershed is moderately urbanized (with 20–30% impervious coverage in the watershed). A factor separation scheme was employed to determine the synergistic effect of land surface and rainfall heterogeneity on flood magnitudes. Increases in flood magnitudes induced by urbanization could be underestimated by as much as 50% if spatial rainfall patterns are ignored. This study highlights the need for considering urban meteorological feedback

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while examining hydrologic responses to urbanization with both the changes of impervious coverage and spatial rainfall patterns considered.

1. Introduction

Hydrologic regimes in urbanized watersheds have been extensively explored in previous studies and continue to be important in an increasingly urbanized world (Arnold and Gibbons, 1996; Leopold, 1968). Urbanization impacts on hydrologic response, especially the flood regimes continue to be an important topic of research (e.g., Pan et al., 2012; Shuster et al., 2005; Smith et al., 2002, 2005; Villarini et al., 2011a; Yang et al., 2013b). The expansion of impervious areas reduces infiltration capacity, enhances direct runoff, and improves the connectivity of flow paths. These changes ultimately modify the magnitude, timing, and duration of floods in urban watersheds. Hydrologic responses to urbanization is important due to its role in the derivation of design flood frequency that most flood management systems build on (e.g., Changnon and Demissie, 1996; Khaliq et al., 2006; Villarini et al., 2009, 2011b). Additionally, changes in urbanization regimes have implications for water quality and water-borne chemical transport (e.g., Klein, 1979; Pickett et al., 2011).

There is now well established evidence regarding the urban modification of rainfall following the benchmark studies as part of METROMEX (Metropolitan Meteorological Experiment, Changnon et al., 1971; Huff and Changnon, 1972). Urban processes such as urban–rural heterogeneities, urban heat island, urban canopy, and urban aerosols can detectably modify rainfall patterns around urban areas (e.g., Bornstein and Lin, 2000; Collier, 2006; Lowry, 1998; Niyogi et al., 2006; Rosenfeld, 2000; Shepherd, 2005; Shepherd et al., 2010). Although some of the key mechanisms remain elusive, it is now understood that the presence of urban surfaces could noticeably change the physical properties of rainfall, including accumulated rainfall, intensity, frequency, dynamic properties of storm evolutions (e.g., structures, tracks, timings,) (Kusaka et al., 2013; National Research Council, 2012; Niyogi et al., 2011; Schmid and Niyogi, 2013; Yang et al., 2013a, 2014).

Since rainfall is the main force that drives surface hydrological processes, the modification of rainfall induced by the presence of urban surface is expected to feedback to the underlying surface processes. It can be further hypothesized that the feedback from rainfall modification will further modify the features of hydrologic responses to urbanization. What is the interactive effect of change in urbanization and the consequent impact on the rainfall patterns on the urban hydrological features has not been addressed in previous studies.

The overarching goal of this study is to investigate the hydrologic responses to urbanization at a watershed scale as a synergistic effect of spatial heterogeneity in rainfall as well as land surface properties. The changes in rainfall distribution in particular have not been adequately considered in prior studies and will be emphasized in this study. Prior studies have shown that the shift of spatial rainfall patterns is a detectable influence of the urban surface (e.g., Li et al., 2011; Lowry, 1998; Yang et al., 2014). This modified rainfall distribution plays an important role in shaping hydrologic responses in watersheds (e.g., Kim and Seo, 2013; Wilson et al., 1979; Yang et al., 2010). For instance, Zoccatelli et al. (2010, 2011) highlighted the connections between spatial rainfall organizations and runoff responses through event-scale modeling studies. The behavior of flood responses could not be accurately captured without the consideration of spatial rainfall variability.

Earlier studies conclude that hydrologic response (e.g., flood magnitude) amplifies with impervious coverage monotonically (e.g., Wright et al., 2012). However, Yang et al. (2010) also suggested that 5% impervious coverage in a watershed could be the minimum threshold, beyond which urbanization begins to affect the hydrologic regimes, and the disturbance intensifies with the increase of impervious coverage. Due to limited samples of urbanized watersheds, previous studies have been unable to examine hydrologic responses to the full stages of urbanization in a watershed (from rural to completely urban, with impervious coverage ranging from 0% to 100%). We hypothesize that hydrologic