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Crossing-scale hydrological impacts of urbanization and climate variability in the Greater Chicago Area

Charles Rougé [a,b], Ximing Cai [a,*]

[a] Ven-Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Avenue, Urbana, IL 61801, United States

[b] Irstea, UR LISC Laboratoire d'ingénierie des systèmes complexes, 9 avenue Blaise Pascal – CS 20085, 63178 Aubière, France

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SUMMARY

This paper uses past hydrological records in Northeastern Illinois to disentangle the combined effects of urban development and climatic variability at different spatial scales in the Greater Chicago Area. A step increase in annual precipitation occurred in Northeastern Illinois during 1965–1972 according to climate records. Urbanization has occurred as a gradual process over the entire Greater Chicago Area, both before and after the abrupt annual precipitation increase. The analysis of streamflow trends at each gaging station is supplemented by the comparison of the evolution of streamflow indicators in a group of urban and agricultural watersheds, thanks to an original use of the Mann–Whitney test. Results suggest that urban expansion in the Greater Chicago Area has led to widespread increases in a wide variety of streamflow metrics, with the exceptions being spring flows and some of the peak flow indicators. The increases detected in small (<100 km^2) urban watersheds are mitigated in large (>200 km^2) ones, over which the changes in streamflow are relatively homogeneous. While the impacts of land-use change are identified across a wide range of flow indicators and spatial scales, there are indications that some of these effects are mitigated or made negligible by other factors. For example, while impervious surfaces are found to increase flooding, stormwater management facilities, an adaptation to increased flooding, mitigate their impacts at a wide range of scales. While impervious surfaces are known to reduce infiltration and baseflow, a low flow increase was triggered by water withdrawals from Lake Michigan, as a response to a rising water demand which made on-site groundwater extraction unsustainable. Our analysis thus highlights the impacts of adaptive planning and management of water resources on urban hydrology.

1. Introduction

With more than half of the world population now living in cities (Grimm et al., 2008), understanding how the growth of a major urban center affects its environmental footprint is crucial to a better management of present and future water resources. Indeed, urban population growth is believed to be one of the major inducers of water stress worldwide by 2025 (Vörösmarty et al., 2000).

The goal of this work is to carry out a statistical analysis of past streamflow records to understand the different impacts of urban development and water resources management across different scales in the greater metropolitan area of a major city, Chicago. Attention will be particularly devoted to observing whether the synthetic effects of land-use changes are in accordance with the observed hydrological results, or if these results show the impacts of water resources development and management practices.

The basic effects of turning natural soils into impervious surfaces have long been documented in the literature. Such land-use change enhances flooding (Hollis, 1975), leads to the depletion of baseflow and low flows through the reduction of infiltration (Ferguson and Suckling, 1990), and increases total discharge through the reduction of evapotranspiration (Dow and DeWalle, 2000). The impacts of urbanization have been explored with simulation models at different spatial scales (e.g. DeWalle et al., 2000; Hejazi and Moglen, 2007; Hejazi and Moglen, 2008; Hejazi and Markus, 2009; Hurkmans et al., 2009).

Meanwhile, interferences to base flows and low flows can also come from water resource management activities such as stream channel alteration, inter-basin transfers, effluent discharge, and/or groundwater pumping (Barringer et al., 1994; Meyer, 2005; Claessens et al., 2006; Wang and Cai, 2009), which are adaptations to urbanization with either socioeconomic or environmental consequences, or both.

Likewise, detention basins can locally mitigate peak flows (Solo-Gabriele and Perkins, 1997; Yeh and Labadie, 1997) and they

* Corresponding author. Tel.: +1 2173334935.
E-mail address: xmcai@uiuc.edu (X. Cai).

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can even play a big role in the watershed's response to rainfall events (Smith et al., 2013). In fact, the effects of these human interferences have countered the effects of land-use change and mitigated or offset them in certain situations (e.g. Barringer et al., 1994; Burns et al., 2005). In the existing literature, however, these effects have all been detected at a single spatial scale, and a complete picture of the consequences of the combined effects of the various water management measures associated with urbanization is not clear. Thus, the overall consequences have not been assessed beyond the scale at which they are detected (e.g. Claessens et al., 2006). In general, it has been argued that interactions between human and natural systems should be investigated crossing scales rather than at a single scale (Liu et al., 2007).

Furthermore, this study also needs to consider the impact of climate fluctuations: a complicating factor when studying human interferences (Claessens et al., 2006; McCormick et al., 2009). Increases in precipitation, in particular in the frequency and magnitude of extreme rainfall events, were reported in the Upper Midwest (Karl and Knight, 1998; Groisman et al., 2004; Pryor et al., 2009; Groisman et al., 2012). Such changes can be linked to climate change (Villarini et al., 2013a) and more precisely with increasing temperatures (Villarini et al., 2013c). Extreme rainfall events have been verified in Chicago (Markus et al., 2007; Villarini et al., 2013b). A wetter climate has been reported to affect the low and mean flows of the Eastern United States (Lins and Slack, 1999; Lins and Slack, 2005), and has accounted for increases in spring and fall precipitation and streamflow in the Upper Midwest (Lettenmaier et al., 1994; Groisman et al., 2001; Small et al., 2006), including Chicago. In fact, the increase in mean annual flow in the Eastern United States has been found to be a step change occurring around 1970 (McCabe and Wolock, 2002), while a similar shift in Illinois water resources has also been documented (Smith and Richman, 1993). Thus, the long-term impacts of climatic variability and those of human interferences must be considered together when looking at streamflow records, as these two types of change can cause distinct temporal patterns, either gradual trends or abrupt steps, with different timings. Examples of this can be found in urbanizing watersheds (Villarini et al., 2009b) or in large river basins, such as the Aral Sea (Glantz, 1999).

In this paper, the main features of climate variability are examined first; following that, the urbanization effects are identified by taking into account the effects of climate variability. Consequently, the present study is to proceed in two steps in order to disentangle the impacts of climate from those of urban development. First, it is to establish the existence of a step increase in rainfall and streamflow in the Greater Chicago Area around 1970, as suggested at greater spatial scales. Second, it is to detect any further gradual changes in streamflow and link them to urban development. Separating a gradual change from an abrupt one within the same time series is a challenging task (Xiong and Guo, 2004). This work attempts to overcome this difficulty in two ways. On one hand, it focuses on distinguishing between the streamflow series where only an abrupt change is present from those where urban development would have more gradual impacts, using, among others, a recent methodological development aimed at making this distinction (Rougé et al., 2013). On the other hand, that same development highlights the challenge to make this distinction based on a single time series; therefore, an original application of the Mann–Whitney test (Mann and Whitney, 1947) extends the paired catchment methodology to paired groups of catchments at the scale of the Greater Chicago Area. Using paired catchments is a classical way of drawing conclusions on different land uses in neighbor catchments where climatic conditions are similar (e.g. Lazaro, 1976; Changnon and Demissie, 1996; Yang et al., 2013). In this work we use the non-parametric Mann–Kendall statistic (Mann, 1945; Kendall, 1975) to represent the temporal evolution of a given streamflow indicator in each basin of each group, then use the Mann–Whitney test to assess the homogeneity of that statistic across both groups.

The rest of this paper is organized as follows. Section 2 presents the shift in precipitation, which is directly related to the streamflow change in the Greater Chicago Area. The configuration of drainage basins and land use are presented in the same section along with the streamflow data, while the methodology for the analysis of streamflow is presented in Section 3. The main temporal patterns discovered in streamflow are outlined in Section 4. Following that, Section 5 discusses the attribution of the observed changes to climate variability and urbanization, in terms of the peak, low, mean, and seasonal flows. Finally, Section 6 concludes this study.

2. Study area: climate and land-use

2.1. Evolution of the regional hydroclimate

Northeastern Illinois (Fig. 1) is reasonably wet and characterized by yearlong rainfall (Milly, 1994b; Sankarasubramanian and Vogel, 2003), with both precipitation and evapotranspiration being higher in summer than in winter (Milly, 1994a). Studies on regional changes in the hydrological cycle since the 1970s are summarized in the introduction. Climate data are now used to understand more accurately the changes of precipitation and temperature in the Greater Chicago Area, because they are likely to impact streamflow. The data sources include monthly National Climatic Data Center (NCDC) data throughout Northeastern Illinois from 1908 to 2007 and local daily and monthly precipitation data from eight NCDC rain gages with long and relatively uninterrupted records (Table 1 and Fig. 1). Besides rainfall data, temperature data are also used to examine whether there is a relation between the changes in temperature and rainfall (Lettenmaier et al., 1994; Groisman et al., 2004; Groisman et al., 2012; Villarini et al., 2013a), or streamflow (e.g. Claessens et al., 2006).

Application of the Pettitt change-point test (Pettitt, 1979) shows a statistically significant ($\alpha = 0.05$) step change in precipitation in 1965. Fig. 2 uses cumulative deviations from the mean of the first part of the record (Buishand, 1982) to display this shift in annual precipitation, also apparent on Fig. 3. The difference between the mean annual precipitation from 1908 to 1964 and 1965 to 2007 is 97 mm annually over the whole Northeastern Illinois climate division of the NCDC. This shift corresponds to a 12% increase in annual precipitation over the whole area. The wettest decades occurred in the 1970s and 1980s (Fig. 3), confirming that the observed change is a step increase rather than a gradual trend. Our examination of data from neighboring NCDC divisions also reveals a wetter climate after 1965. However, this step increase in precipitation is not linked to rising temperatures. In reality, it is associated with complex seasonal fluctuations at the decadal time scale (Fig. 3), consistent with recent findings from Ryberg et al. (2014) in the North Central United States. For instance, the two wettest decades, 1968–1977 and 1978–1987, are the respective consequence of decade-long maxima for spring and for summer and fall precipitation. Note that the four seasons are defined within the present work as three-month periods during a calendar year.

At the local level, the analysis for the eight rainfall gages demonstrates that there has been a wetter climate after 1965 than before, with an increase of 70 mm annually. It also shows significant spatial correlation of precipitation throughout the study area. However, strong local discrepancies exist. For instance, although six out of eight gages display a uniform temporal shift in the mean, the two other ones (Joliet in the south part of the area and Waukegan in the north) display rainfall levels during the late