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Slowflow fingerprints of urban hydrology

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SUMMARY

Urban streamflow is commonly characterized by increased peak discharges and runoff volumes. Slowflow integrates altered storage and transit times affecting urban recharge and drainage, resulting in a highly variable indeterminate urban slowflow response. This study introduces the use of multiple baseflow metrics to characterize and interpret the dominant processes driving urban slowflow response. Slowflow characteristics derived from USGS streamflow records are used to quantify the patterns of hydrologic alteration across the rural-to-urban landuse gradient in the Piedmont watersheds of the Baltimore Ecosystem Study (BES), an NSF Urban Long Term Ecological Research (LTER) site in the Baltimore Metropolitan area. We interpret multimetric slowflow response from a top-down perspective, learning from data, in order to draw dominant process inferences from observed slowflow. When characterized by a single slowflow metric such as the baseflow index, urban slowflow response can exhibit equifinality and is not reliably predicted *a priori*. Multimetric analysis quantifies distinct differences in urban slowflow response, framing testable hypotheses and refined experimental designs to elucidate the dominant processes driving urban slowflow. Multimetric fingerprinting offers a consistent framework for interpreting urban slowflow response, constrained by the equifinality of single slowflow metrics and the inherent limitations on process inferences that can be drawn from gauged streamflow alone. Heterogeneity of observed slowflow belies the simple paradigm of a single consistent type of urban slowflow response. In contrast, we suggest a conceptual typology of urban slowflow response, framing a conceptual mixing model of dominant process endpoints that shape the slowflow fingerprints of urban hydrology.

1. Introduction

Urbanization can change basin water budgets by (a) altering the distribution of vegetation, pervious and impervious landuses, and the overall landscape drainage pattern; (b) increasing withdrawals from surface and groundwater systems that support human needs; and (c) re-engineering the water budget through water and wastewater infrastructure and interbasin water transfers that can alter both recharge and subsurface drainage (Claessens et al., 2006; Dougherty et al., 2007; Elmore and Kaushal, 2008; Hibbs and Sharp, 2012). The cumulative effect of these interacting processes changes watershed-scale storage and transit times, imprinting the hydrologic signature of human activities on urban streamflow response. Conceptually, the hydrologic impact of urbanization is most commonly associated with an intensified quickflow response attributed to the combined effects of increased runoff from impervious surfaces and efficient drainage infrastructure, with accompanying decreases expected in infiltration, recharge, soil moisture, and baseflow (Boggs and Sun, 2011; Brander et al., 2004; Burns et al., 2012; Walsh et al., 2005). Changes among the processes driving urban hydrologic response can be highly variable and uncertain. In contrast to the process-based characterization implied by the terms runoff and baseflow, the components of the observed hydrograph are commonly referred to as quickflow and slowflow, acknowledging the uncertain mixture of processes generating observed streamflow (Carey and Woo, 2001; Hansen et al., 1996; Post and Jakeman, 1996). Here and throughout we refer to quickflow and slowflow to distinguish distinct fast response and slow response components of observed streamflow, independent of any inferences or assumptions about underlying hydrologic processes.

Slowflow response integrates the changes in dominant watershed processes that accompany urbanization. Shallow groundwater pumping can lower the water table impairing baseflow, even as return flows from deep groundwater withdrawals can introduce recharge originating outside the watershed boundary, effectively creating an interbasin transfer through deep aquifers. Steady return flows from wastewater discharges can enhance observed baseflow response without affecting the groundwater

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system. The hydrologic response to urbanization is not reliably predicted *a priori*, without catchment-specific understanding of the dominant processes driving observed discharge.

This study introduces the use of multiple baseflow metrics to characterize and interpret the observed slowflow response of urban watersheds. In contrast to traditional "bottom-up" reductionist modeling approaches we embrace a top-down perspective (Sivapalan et al., 2003), inferring the dominant processes driving the heterogeneity of urban slowflow. Observed slowflow differences are identified and interpreted using a consistent multimetric fingerprint derived from USGS daily streamflow data. We demonstrate multimetric slowflow analysis for the Piedmont watersheds along the rural-to-urban landuse gradient of the Baltimore Ecosystem (BES) Long Term Ecological Research (LTER) site (Pickett and Cadenasso, 2006). The slowflow response of a set of representative reference watersheds selected from the USGS GAGES-II database (Falcone, 2011; Falcone et al., 2010) provides a regional physiographic and hydroclimatic template for comparable watersheds that are least impacted by human alteration. Slowflow metrics standardized to the mean reference set response, define multimetric fingerprints of the BES watersheds.

The following section reviews urbanization's effects on both quickflow and slowflow, motivating the interpretation of slowflow response using multiple streamflow metrics. Section 3 describes the multimetric framework used to characterize the slowflow response of the BES watersheds. Section 4 presents the results of this multimetric analysis, elucidating the heterogeneity and equifinality of slowflow responses manifested by the BES watersheds. The inference and expression of the dominant processes driving urban slowflow response is discussed in Section 5. We propose a typology of urban slowflow response, framing the interpretation of observed slowflow through a conceptual hydrologic mixing model of dominant process endpoints. Conclusions are presented in Section 6.

2. Background

2.1. Hydrologic effects of urbanization

Urbanization is commonly expected to alter quickflow, increasing the runoff ratio (the fraction of precipitation producing runoff) and peak discharge (Beighley and Moglen, 2002; Farahmand et al., 2007; Huang et al., 2008). For closed water budgets, increased urban runoff is usually expected to decrease baseflow and the baseflow index (BFI, the ratio of baseflow to discharge) due to reduced recharge (Leopold, 1968). Indeed, low BFI values are commonly ascribed to urbanized streams.

Dramatic changes in quickflow response defined engineering hydrology's historical focus on urban flooding, drainage, and changes in peak flows and flood frequencies (Beighley and Moglen, 2002, 2003; Fok et al., 1975; Hollis, 1975; James, 1965; Konrad, 2003; Kuichling, 1889; Lloyd-Davies, 1906; Ramey, 1959; Wilson, 1967). Yet even the early urban hydrology literature (focused on drainage, increased peak discharges, and urban flooding) also recognized changes in infiltration, evapotranspiration (ET), and interbasin transfers as significant hydrologic impacts that accompany urbanization and mediate urban hydrologic responses (Fok et al., 1975; Waananen, 1969). Leaking infrastructure, interbasin transfers, and both hydroclimatic and anthropogenic influences (*sensu* Brandes et al. (2005)), contribute to the heterogeneity of urban hydrologic response. In practice, widely varying baseflow responses integrate and reflect the inherent variability of hydrologic storage and transit times in urban watersheds. The simple conceptual model of a single distinctive urban baseflow response is not consistently observed in urban watersheds (Brandes et al., 2005; Hubbart and Zell, 2013; Meyer, 2005). Rather, urbanization yields an indeterminate baseflow response (Hamel et al., 2013; Price, 2011) that cannot be reliably predicted from simple measures of urbanization such as impervious area (Arnold and Gibbons, 1996).

The direct effects of urbanization are accompanied by secondary development impacts associated with distributed water and wastewater infrastructure (Lerner, 2002; Pluhowski and Spinello, 1978; Wittenberg and Aksoy, 2010). The secondary effects of water and wastewater infrastructure can moderate urban hydrologic response through leaking infrastructure, wastewater discharges, interbasin transfers through both municipal water supply and regional wastewater systems, and groundwater withdrawals. Leakage and exfiltration from aging infrastructure can significantly increase effective annual recharge, raising regional water tables and increasing baseflow (Lerner, 2002). Low to moderate density development with significant disconnected impervious areas can increase concentrated recharge (Brandes et al., 2005; Holman-Dodds et al., 2003).

Baseflow is commonly conceptualized as groundwater drainage from a linear or non-linear lumped parameter reservoir (Botter et al., 2009; Buytaert et al., 2004; Datta et al., 2012; Fenicia et al., 2006; Harman et al., 2009; Wittenberg, 1999). A more nuanced conceptual model considers baseflow as the cumulative response of the coupled groundwater-surface water system, integrating both hydrologic changes to the water balance and hydraulic changes to drainage characteristics. Hydrologic changes can include reduced evapotranspiration (ET) (Wang and Cai, 2010) as impervious surfaces replace vegetated landcover; groundwater pumping that lowers the water table; and both recharge and drainage from leaking water infrastructure that commonly create regional interbasin water transfers. Slowflow response also integrates processes such as steady wastewater discharges that alter the observed slowflow response but bypass the groundwater system entirely. Beyond these hydrologic effects, infiltration and inflow to unpressurized sewer infrastructure can accelerate groundwater drainage, altering the watershed's effective hydraulic response and changing the observed baseflow recession constant.

Baseflow integrates watershed-scale hydrologic forcings and cumulative landscape changes. No single baseflow measure – such as the BFI or regional recharge estimates – can fully capture or uniquely resolve the complex hydrologic changes that accompany urbanization. Different combinations of dominant processes can yield similar responses in a single slowflow metric (equifinality) even as the heterogeneity of urban watersheds yields an indeterminate slowflow response (Hamel et al., 2013; Price, 2011). We embrace the perspective that dominant process information can be inferred from the observed discharge hydrograph (Wagener et al., 2007), interpreting the heterogeneity and equifinality of urban slowflow response through a consistent set of slowflow metrics derived from gauged streamflow.

2.2. Multimetric baseflow analysis

Sawicz et al. (2011) used multivariate streamflow signatures to group hydrologically similar catchments in the Eastern United States, focusing on differences between the process controls and variability of empirical streamflow signatures. We similarly use multiple baseflow metrics to distinguish multivariate differences in urban baseflow response. Like Sawicz et al. (2011), we recognize the inherent limitations of using streamflow analysis alone to fully resolve the dominant processes controlling observed discharge. Complementary methods using, e.g., stable isotopes and other chemical tracers (Burns and Kendall, 2002; Christian et al., 2011; Gremillion et al., 2000; Kaushal et al., 2011; Kracht et al., 2007; Nolan et al., 2007) can enrich the process-based understanding of baseflow sources, residence times and flow paths in ways that