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Research papers

Urbanisation impacts on storm runoff along a rural-urban gradient

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A B S T R A C T

Urbanisation alters the hydrological response of catchments to storm events and spatial measures of urban extent and imperviousness are routinely used in hydrological modelling and attribution of runoff response to land use changes. This study evaluates whether a measure of catchment urban extent can account for differences in runoff generation from storm events along an rural-urban gradient. We employed a high-resolution monitoring network across 8 catchments in the south of the UK - ranging from predominantly rural to heavily urbanised - over a four year period, and from this selected 336 storm events. Hydrological response was compared using volume- and scaled time-based hydrograph metrics within a statistical framework that considered the effect of antecedent soil moisture. Clear differences were found between rural and urban catchments, however above a certain threshold of urban extent runoff volume was relatively unaffected by changes and runoff response times were highly variable between catchments due to additional hydraulic controls. Results indicate a spatial measure of urbanisation can generally explain differences in the hydrological response between rural and urban catchments but is insufficient to explain differences between urban catchments along an urban gradient. Antecedent soil moisture alters the volume and timing of runoff generated in catchments with large rural areas, but was not found to affect the runoff response where developed areas are much greater. The results of this study suggest some generalised relationships between urbanisation and storm runoff are not represented in observed storm events and point to limitations in using a simplified representations of the urban environment for attribution of storm runoff in small urban catchments. The study points to the need for enhanced hydrologically relevant catchment descriptors specific to small urban catchments and more focused research on the role of urban soils and soil moisture in storm runoff generation in mixed land-use catchments.

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1. Introduction

Urban development brings an increase in impervious surfaces that reduces rainfall infiltration to underlying soils and surface storage capacity (Booth, 1991) with a concomitant rise in the degree of artificial drainage that acts to convey runoff through more efficient pathways (Boyd et al., 1994). The combined effects include an increase in storm runoff (Burn and Boorman, 1993) and volume (Kjeldsen et al., 2013), reduction in baseflows (Simmons and Reynolds, 2013) and shortening of catchment response times (Smith et al., 2005; Anderson, 1970) resulting in a more flashy response (Baker et al., 2004). Urbanisation thus presents a particular challenge to planners as the development of previously rural or low urban density catchments will potentially alter the rainfall-runoff response and require careful planning to manage the changes in the timing and quantity of water moving through the catchment. Coupled with projected increased frequency of extreme rainfall events as a result of climate change, this poses a significant environmental risk in the form of pluvial and fluvial flooding (Bell et al., 2012; Eigenbrod et al., 2011; Poelmans et al., 2011).

Many studies on the hydrological impacts of urbanisation have been based on field observations (e.g. Hood et al., 2007; Kauffman et al., 2009; Sheeder et al., 2003) and increasingly utilise models calibrated to observations (Bach et al., 2014). In both cases, suitable hydrological metrics are required to quantify hydrological response and subsequently attribute response to differences in land use. Arbitrary flow statistics are not always suitable for quantifying the hydrological impacts of land-use change (LUC) (Mcintyre et al., 2013) and for urban storm events, Braud et al.

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(2013) show the storm hydrograph provides the most suitable means for comparing hydrological response. In addition, relevant information describing how the catchment differs from a control or baseline condition is required. LUC in urban areas is highly complex and as such the diversity of the urban fabric is generally represented by either: urban land-use type (e.g. urban/suburban: Morton et al., 2011), density of urban development (e.g. dwelling units per acre: Jacob and Lopez, 2009), and most generally imperviousness (Arnold and Gibbons, 1996; Dams et al., 2013).

While impervious surfaces are important for driving urban runoff, permeable surfaces still have an important role in urban catchments (Berthier et al., 2004) and can make up a considerable portion of the catchment area. In UK cities, gardens alone account for between 22% and 27% of city area (Loram et al., 2007). The partitioning of precipitation between runoff and infiltration on pervious soils is affected by soil type (Boorman et al., 1995) and the soil-moisture state of the soil (Brady, 1984), but in urban areas factors such as compaction have also been shown to significantly alter the hydrological response (Yang and Zhang, 2011). Antecedent soil moisture has been shown to have variable impacts upon runoff across different urban surfaces and in different soil-moisture states (Hollis and Ovenden, 1988; Hood et al., 2007; Smith et al., 2013; Ragab et al., 2003) leading to considerable uncertainty when modelling the hydrological response of mixed urban-rural catchments (Kjeldsen et al., 2013). Given the current interest in the role of soils in urban catchments as part of green infrastructure to control storm runoff and reduce flooding (Kelly, 2016; POST, 2016) this uncertainty highlights a pressing need to better understand the role of soil moisture in urban soils in altering the impacts of urbanisation on runoff from storm events.

The relationship between urbanisation and storm runoff on the basis of change in impervious area has become generalised in lumped hydrological model structures (e.g. ReFH: Kjeldsen, 2007) to characterise the urban environment (Salvadore et al., 2015). However, despite early indications that impervious area alone is insufficient to explain catchment response (Hall, 1977), there has been limited empirical research (e.g. Braud et al., 2013; Sillanpää and Koivusalo, 2015) on the link between urbanisation and storm runoff across a suitable range of hydrological metrics. While there have been a number of studies investigating ecological diversity along an rural-urban gradient (e.g. McDonnell et al., 1997; Clergeau et al., 1998; Kroll et al., 2012) few have investigated hydrological response along an rural-urban gradient (e.g. Schoonover and Lockaby, 2006). The objectives of this study, therefore, are to assess: (i) whether a lumped-catchment spatial measure of urbanisation can explain the observed variability in catchment response to storm events along a rural-urban gradient; and (ii) the extent to which antecedent soil moisture conditions modify that relationship. These objectives provide the structural sub-headings used the following Methods, Results and Discussions sections.

2. Study sites

The Thames basin in southern England (Fig. 1) is the largest drainage basin in the UK (Crooks and Kay, 2015) and has a temperate mid-latitude climate. The basin contains the rapidly urbanising towns of Swindon (Population 210,000) and Bracknell (Population 77,000). Both are located in low-lying river catchments gauged by the Environment Agency (EA) at Water Eaton (station number 39087) and Binfield (station number 39052) respectively. High spatial and temporal resolution monitoring of flow and precipitation was undertaken over a four year period from May 2011 to October 2015 across eight independent sub-catchments within these two river catchments (Fig. 1; Table 1).

3. Methods

3.1. Hydro-meteorological urban monitoring networks

Precipitation was monitored at 8 locations (shown as Raingauge in Fig. 1) at a 15 min resolution with tipping bucket raingauges (Casella TBRG), with network design following BSI (2012a). Data were quality controlled for errors relating to low/high intensity, missing data, and synchronization between sensors, following national (BSI, 2012b) and international guidelines (WMO, 1994, 2008). Additional 15 min rainfall data from tipping bucket raingauges located within the catchment at Swindon (R249744) and close to the catchment boundary at Bracknell (R274918), were provided by the EA (shown as EA raingauge in Fig. 1). These are quality controlled and in-filled using observations from a national network, and provided a continuous and robust source of data for in-filling and calibration of monitoring raingauge observations when data were missing or erroneous. Estimates of areal rainfall for both catchments were obtained using arithmetic and Thiessen polygon weighting methods (BSI, 2012b). The Thiessen polygon approach, widely used in urban hydrological studies (e.g. Blume et al., 2007a,b; Yue and Hashino, 2000), was found suitable for Swindon due to the distribution of monitoring raingauges and central location of the EA gauge relative to the study-sub-catchments. For Bracknell the arithmetic mean was judged to be more appropriate due a number of factors including: i) the relative size of the study area and overall distribution of observation gauges across the catchment (BSI, 2012b), ii) recurring issues of under-catch or tampering for observation gauges; and iii) the overall effect of a low weight applied to the EA gauge if the Thiessen polygon approach was used (being located outside of the study sub-catchments – see Fig. 1) which significantly reduced observation accuracy relative to this gauge.

Discharge was monitored at 5 min resolution using ultrasonic Doppler shift instruments (Unidata Starflow 6526H), with a velocity and depth accuracy of ±2% and ±0.25% respectively, mounted to the bed of suitable hydraulic structures according to ISO (2010). Depth and velocity data were quality controlled, and processed using measured cross sections to derive flow using the methods outlined by Blake and Packman (2008). Ratings developed from spot-gaugings of depth and flow (SonTek FlowTracker) were used to calibrate observations of depth and velocity across the channel cross section, and increase accuracy. Additional concurrent flow data at a 15 min resolution for each catchment outlet EA gauging station (39087, 39052: Fig. 1) were provided by the EA.

3.2. Objective 1: Hydrological response along a rural-urban gradient

3.2.1. Catchment characterization

Catchment descriptors (Table 2) for the EA catchments and the selected study catchments were obtained from the UK Flood Estimation Handbook (FEH) web service (https://fehweb.ceh.ac.uk/). These indicate that the catchments are sufficiently similar in altitude (ALTBAR), climate (SAAR; RMED-1H), soil (SPRHOST, PROPWET), and baseflow indices (BFIHOST) to allow comparison among the study sub-catchments. Catchment area was determined using a combination of a 10 m resolution digital terrain model (DTM) and storm drainage mapping to accurately identify catchment boundaries as these can be altered by urban development and artificial drainage (Braud et al., 2013). The study catchments differ geomorphically in area (AREA), slope (DPSBAR) and mean drainage path length (DPLBAR), while the predominant difference in land use was in terms of urban extent (URBEXT). Although the Bracknell study catchments have slightly higher levels of pond/

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