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Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover

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SUMMARY

This paper investigates changes in storm runoff resulting from the transformation of previously rural landscapes into peri-urban areas. Two adjacent catchments (~5 km^2) located within the town of Swindon in the United Kingdom were monitored during 2011 and 2012 providing continuous records of rainfall, runoff and actual evaporation. One catchment is highly urbanized and the other is a recently developed peri-urban area containing two distinct areas of drainage: one with mixed natural and storm drainage pathways, the other entirely storm drainage. Comparison of observed storm hydrographs showed that the degree of area serviced by storm drainage was a stronger determinant of storm runoff response than either impervious area or development type and that little distinction in hydrological response exists between urban and peri-urban developments of similar impervious cover when no significant hydraulic alteration is present. Historical levels of urbanization and impervious cover were mapped from the 1960s to the 2010s based on digitized historical topographic maps and were combined with a hydrological model to enable backcasting of the present day storm runoff response to that of the catchments in their earlier states. Results from the peri-urban catchment showed an increase in impervious cover from 11% in the 1960s to 44% in 2010s, and introduction of a large-scale storm drainage system in the early 2000s, was accompanied by a 50% reduction in the Muskingum routing parameter *k*, reducing the characteristic flood duration by over 50% while increasing peak flow by over 400%. Comparisons with changes in storm runoff response in the more urban area suggest that the relative increase in peak flows and reduction in flood duration and response time of a catchment is greatest at low levels of urbanization and that the introduction of storm water conveyance systems significantly increases the flashiness of storm runoff above that attributed to impervious area alone.

This study demonstrates that careful consideration is required when using impervious cover data within hydrological models and when designing flood mitigation measures, particularly in peri-urban areas where a widespread loss in pervious surfaces and alteration of drainage pathways can significantly alter the storm runoff response. Recommendations include utilizing more refined urban land use typologies that can better represent physical alteration of hydrological pathways.

1. Introduction

Growing populations and migration towards built areas is driving land use change in the form of urbanization across the globe and by 2050 some 70% of the world's population are expected to live in urban areas (UN, 2008). The population of the United Kingdom is projected to increase by 9.6 million over the next 25 years from an estimated 63.7 million in 2012 to 73.3 million in 2037 (ONS, 2012), requiring significant new housing stock that cannot always be developed within existing urban areas or on Brownfield[1]

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[1] The term 'Brownfield' refers to abandoned or underused post industrial and commercial areas available for re-development.

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sites. A significant proportion of the growth will be met by an expansion of the peri-urban environment – defined as 'the space around cities that merges into the rural landscape' (Piorr et al., 2011). Contemporary planning policy within the United Kingdom (Department for Communities and Local Government, 2012) reflects this, recommending that the supply of new homes can sometimes best be achieved through large scale new developments or extensions to existing settlements.

Urbanization brings with it a range of environmental challenges for both the local, regional and wider environment as a direct result of the biochemical and physical changes to hydrological systems (Fletcher et al., 2013; Jacobson, 2011). The loss in pervious surfaces reduces the infiltration into soils, while the introduction of artificial drainage replaces natural pathways. This combination is generally considered to have considerable effect on the hydrological response of an area to rainfall, such as: faster response (Huang et al., 2008), greater magnitude of river flow (Hawley and Bledsoe, 2011), higher recurrence of small floods (Hollis, 1975; Braud et al., 2013a), reduced baseflow and groundwater recharge (Simmons and Reynolds, 1982). The reality is often further complicated by the installation of storm water retention systems, and the import/export of water to and from a catchment. For example, some studies suggest leakage from water mains can sustain baseflow during dry periods, while storm water drains coupled with retention features can attenuate flows (Scholz and Yazdi, 2009).

Much of the available evidence on the long-term hydrological effects of urbanization has been obtained through the application of hydrological models (Fletcher et al., 2013). Such models facilitate the manipulation of temporal and spatial physical changes in order to ascertain the resulting impacts on the simulated hydrological response, in particular the impacts of land-use change (LUC) and growth in impervious cover. However, model based studies of LUC impacts are typically based on spatial datasets consisting of limited urban land-use classifications that could neglect the imperviousness of the urban fabric. Furthermore, few studies have been able to reconstruct long-term historical LUC (e.g. Gerard et al., 2010; Tavares et al., 2012). Consequently, hydrological models are often based on parameterization of land use at inappropriate spatial and temporal scales or classification (Dams et al., 2009). Recently published studies show that it is more appropriate and cost-effective to utilize remote sensing data to provide spatially consistent values for imperviousness (e.g. Burges et al., 1998; Canters et al., 2011; Chormanski et al., 2008), and that effective impervious area and spatial-connectivity are accompanying factors that have been demonstrated as hydrologically important for modelling urban runoff (e.g. Han and Burian, 2009; Mejia and Moglen, 2009). However, the reliance upon remote sensing data, which is not always available for earlier decades, means that past LUC or impervious cover cannot be accurately reconstructed and therefore the ability to assess the hydrological impacts of urbanization is limited.

Despite the current and potential growth in peri-urban areas few scientific studies have paid particular attention to the hydrological impacts of widespread urbanization on previously rural areas. Recent work by Braud et al. (2013a), based on relatively long-term observations, confirms that many of the accepted theories regarding urbanization are evident in the changing hydrological regime of a selected peri-urban area, such as reduced baseflow and reduced lag-times resulting in more 'flashy' flood hydrographs from urban areas. Perrin et al. (2001) studied a small peri-urban catchment in the South-American Andes and found that urbanized areas were the primary driver of storm runoff. However, both studies highlight the complexities in isolating land use change impacts in a real catchment with diverse land-use and hydrological pathways. In addition, the complexity of catchments having a mix of fast and slow hydrologic response as a result of combining artificial with natural flow pathways (Braud et al., 2013b) adds further complexity to the task of attribution.

The aim of this study is to determine whether a high level of peri-urban development upon a previously rural area has led to significant increases in peak flows and reduced response time and to determine the differential impacts of mixed runoff pathways and development type on generation of storm runoff. This will be achieved through three successive steps. First, observations from monitoring of two adjacent catchments are utilized to characterize storm runoff response from different types of development. Next, the temporal and spatial change in urban extent and imperviousness within the catchments is mapped for each decade between 1960 and 2010. Finally, a semi-distributed hydrological model is calibrated and validated against observed storm runoff, and subsequently used to backcast and investigate how the urbanization process has impacted the storm runoff response over the historical period of development. The observations and modelling are focusing on two urbanized catchments draining parts of Swindon town, located in the south-west of England. The results of this study are discussed to inform upon the impacts of peri-urbanization on the generation of storm runoff and to highlight appropriate mitigation measures.

2. The study area

This case study utilizes the data obtained from hydrological monitoring of two adjacent catchments of similar size (~5 km^2) located in the north of Swindon town (Fig. 1), that have undergone contrasting patterns of development during the last 50 years (~1960–2010). Both the Haydon Wick brook and Rodbourne stream are tributaries of the larger River Ray, itself a tributary to the upper reaches of the River Thames. Catchment slope was derived from a 2 m resolution Digital Elevation Model (DEM) and indicates both catchments are generally of shallow slope with altitude varying between 85 and 150 m Above Observable Datum (AOD). Geological mapping indicates that the lower part of the Haydon Wick catchment is dominated by mudstone formations, while the upper areas are composed of sandstone and limestone. The Rodbourne catchment is almost entirely underlain by mudstone. Soil sample analysis and borehole records indicate a wide variety of surface soil compositions across the study area and typically shallow soils.

Swindon is a typical example of a post-war London satellite town developed under the Town Development Act of 1952. The historical village area had previously been extended as a railway town in the 19th century, but the late 20th century development brought significant urbanization of centralized areas containing extensive commercial and industrial developments along with peri-urbanization of surrounding rural villages. Land use and cover data, as detailed by the UK wide Land Cover Map 2007 (Morton et al., 2011), indicates significant urban and suburban development interspersed with urban green spaces within housing estates and along stream corridors.

The Rodbourne (ROD) catchment contains a highly urbanized area along the Rodbourne stream receiving runoff from central commercial and industrial areas along with pockets of dense suburban housing. The monitored part of the Rodbourne catchment (Area 5.5 km^2) represents an area that has been extensively developed since before $c \sim 1960$ and includes areas of combined foul and surface water drainage, where storm flows are conveyed to a major sewage treatment works that discharges into the main River Ray catchment. This treatment works contains storage to accommodate moderate storm flows from areas of central Swindon that can bypass the monitored site during high flows, however no