Refining flood estimation in urbanized catchments using landscape metrics

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\begin{abstract}
Flood estimation methods in ungauged basins rely upon generalized relationships between flows and catchment properties. Generally such catchment properties are based on low-resolution national datasets from low density urbanized basins and do not consider location, connectivity and patch size. Such factors are more routinely represented in landscape metrics employed in ecology, and could be particularly useful for representing the diversity of urban land-use. Here, hydrologically relevant landscape metrics are brought together with refined land-use classes and catchment descriptors routinely applied in UK flood estimation methods to estimate the median annual flood (QMED) in order to evaluate the potential role of such metrics. The results show that using higher resolution geospatial data can improve the representation of the urban environment, having particular effects on the delineation of urban water features and catchment area, but not urban extent. Refinement of landscape metrics based on correlations resulted in 12 metrics and 5 catchment descriptors being tested against observed QMED at 18 sites using a weighted least squares regression. The revised equation showed that certain landscape metrics can better represent the hydrological complexity of an urban catchment in a single distributed numerical form, leading to improved estimates of QMED over non-distributed descriptors, for the selected case-study sites. The ability of landscape metrics to express connectivity and relative size and location of urban development promises significant potential for application in urban flood estimation and catchment-scale hydrological modelling.
\end{abstract}

\section{Introduction}

The process of urbanization entails a progressive loss of agriculture and natural habitat, converting pervious soil surfaces and natural drainage into impervious surfaces serviced by artificial drainage. These changes have a particular effect upon the storm runoff response of catchments, whereby impervious surfaces act to reduce soil infiltration and increase surface runoff (Jacobson, 2011), and artificial drainage speeds up the conveyance of runoff and the connectivity of urban surfaces to drainage channels (Shuster, Bonta, Thurston, Warnemuende, & Smith, 2005). This can increase the risk of flooding through higher peak flows (Hawley & Bledsoe, 2011) greater volumes (Packman, 1980) and more frequent flooding (Braud et al., 2013).

In order to quantify the impacts of urbanization on the environment some form of classification or quantification of the urban fabric is required, for example, both the UK Countryside Survey (http://www.countrysidesurvey.org.uk/) and UK Flood Estimation Handbook (FEH) methods (Institute of Hydrology, 1999) rely upon a temporal range of UK wide Land Cover Mapping (LCM) products (Morton et al., 2011). Hydrological quantification of the urban environment can be derived from land use classes with variations based on density, for example, low-high density residential (Gallo, Brooks, Lohse, & McLain, 2013) or using classes to derive an index of urbanization, for example, the catchment index of urban extent (URBEXT: Bayliss, Black, Fava-Verde, & Kjeldsen, 2006). These both provide an index of catchment imperviousness, or total impervious area (TIA), which is increasingly being directly measured using remotely sensed data to facilitate an enhanced representation of the urban environment (Weng, 2012), often for use in high-resolution hydrological modelling (Salvadore, Bronders, & Batelaan, 2015). Combining remote sensing imagery with other spatial data has proven particularly effective at determining how connected urban surfaces are to storm drainage, producing indicators such as directly connected impervious area (DCIA) (Roy & Shuster, 2009) or effective impervious area (EIA) (Janke, Gulliver, & Wilson, 2011). However such detail is not always required at catchment scales (> 0.25 ha) where TIA is sufficiently accurate for estimating DCIA across multiple developed parcels in certain applications (Roy & Shuster, 2009) and URBEXT can be a direct index of imperviousness (Miller & Grebby, 2014). At national scales class based mapping remains more readily available and routinely used, particularly as it can

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offer historical picture of change. Progress is however being made across the globe in national mapping of imperviousness and temporal change, from Europe (EEA, 2016) to India (Wang, Huang, & Brown de Colstoun, 2017) and USA (Wickham et al., 2013).

For national methods of flood estimation at ungauged sites, there remains in many countries a reliance on the simplicity of empirical formulae relating the index flood to catchment characteristics (Bocchiola, Michele, & Rosso, 2003) that include land class data to inform upon levels of imperviousness for more urbanized locations (Formetta, Prosdocimi, Stewart, & Bell, 2017). National agencies across Europe continue to employ such methods (Castellarin et al., 2012), based on regressions of index flood data to catchment characteristics in gauged basins. When considering more urbanized catchments, research has additionally highlighted the need to consider connectivity and location relative to the catchment outlet and scale considered (Kjeldsen, Miller, & Packman, 2013; Miller et al., 2014; Sillanpää & Koivusalo, 2015). For example, in the UK, where such descriptors are routinely used to estimate the median annual flood (QMED), both Vesuviano et al. (2016) and Faulkner, Kjeldsen, Packman, and Stewart. L. (2012) find that existing descriptors and equations perform with less certainty in small urbanized catchments compared to rural catchments. Further, Miller and Hess (2017) find a non-distributed measure such as imperviousness does not mirror the variation in peak flows between urban catchments potentially driven by spatial layout. Thus, while imperviousness is important, class data remain employed for its estimation, and as Mejía and Moglen (2009) show, it is equally important to consider the spatial distribution of impervious land cover, as this can have consequences for the resulting flood peaks.

Spatial or landscape metrics are a tool for quantifying structure and pattern in thematic data, and have been highlighted by Herold, Couclelis, and Clarke (2005) and Ogden, Raj Fradhan, Downer, and Zahner (2011) as valuable for improving representations of urban hydrological dynamics. The use of landscape metrics in hydrology has however been limited, despite showing promise in predicting urban land-use change impacts through representation of form and function (Lin, Hong, Wu, Wu, & Verburg, 2007; Van de Voorde et al., 2016). Comparatively, urban ecological research, which has long been using ecological typologies to study ecosystem dynamics (Brady et al., 1979), has evolved into many detailed landscape metrics of landscape structure in dedicated spatial statistical software (Kupfer, 2012) with diverse applications (e.g. Alberti, 2005; Jiao, 2015; Muhs, Herold, Meinel, Burhardt, & Kretschmer, 2016). Within ecological landscape metrics, distance is often considered as Euclidean and thus is not calculated according to a hydrological network. The importance of hydrological distance to catchment outlet is demonstrated by Van Nieuwenhuysen, Antoine, Wyseure, and Govers (2011), yet while aggregation based landscapes metrics have been tested for hydrological applications, and shown to be effective at providing an estimate for connectivity (Yang, Bowling, Cherkauer, & Pijanowski, 2011), there have been few efforts to consider hydrological distance. Wan Jaafar and Han (2012) have shown the potential for improving QMED using more hydrologically relevant descriptors to be derived from catchment form and information on land cover.

Local scale hydraulic features are increasingly being installed within the urban environment to control runoff, such as sustainable urban drainage systems (SuDS) (Woods Ballard et al., 2015). Studies suggest features such as green roofs (Vesuviano, Sonnenwald, & Stovin, 2014), offline storage (Wilkinson, Quinn, & Welton, 2010) and plot-scale bio-retention features (Hood, Claussen, & Warner, 2007) reduce and attenuate runoff, but such features are not routinely mapped. Additionally, attenuation of runoff as baseflow (Rivet, Ellis, & Mackay, 2011) can be altered by soil management (Holman, Hess, & Rose, 2011) and evidence suggests that soils in urban areas can be so degraded through compaction and decreased hydraulic conductivity (Chen, Day, Wick, & McGuire, 2014) that infiltration potential approaches that of impervious surfaces (Gregory, Dukes, Jones, & Miller, 2006) and increases runoff (Yang & Zhang, 2011). There are, however, currently no distinctions made in Land Cover Map (LCM) grassland classes between such surfaces (Morton et al., 2011). Conversely there is evidence that improving soil condition will improve infiltration (Chen et al., 2014) and better management of the urban landscape can provide green infrastructure (GI) and ecosystem services (Tratalos, Fuller, Warren, et al., 2007) that reduce runoff volumes (Shuster, Dadio, Drohan, Losco, & Shaffer, 2014). Infiltration and local storage is also much improved in areas of preserved or managed nature and woodland (Nisbet TR, 2006). Again, given the potential role of SuDS and GI for flood attenuation, there is surprisingly little attention paid to mapping such land-use and testing its effect on urban runoff. There is however a growing body of research mapping GI, based on using remote sensing data (Liquete, Kleeschulte, Dige, et al., 2015; Vatseva et al., 2016) and developing a comprehensive classification of GI (Koc, 2017). Given these recent advances, and recent GI interest in both the UK (Kelly, 2016; POST., 2016) and internationally (Jarden, Jefferson, & Grieser, 2015), the lack of consideration regarding the functionality of SuDS and green space as GI, is clearly an area that should be expanded upon (Gill, Handley, Ennos, & Pauleit, 2007).

This study aims to use high-resolution spatial data alongside refined urban land cover classes from a UK case study to derive spatial landscape metrics and assess the potential application of landscape metrics for estimating the index flood in urbanized catchments. For this, three objectives are set: i) develop a set of hydrologically relevant urban land-use classes that can be mapped using readily available geo-spatial information, ii) derive enhanced urbanized catchment descriptors and identify suitable landscape metrics for use in flood estimation within the United Kingdom, and iii) test the performance of updated catchment descriptors and landscape metrics for estimating QMED for selected study catchments compared with existing flood estimation methods. This will inform the potential for developing a wider method using spatial metrics and remote sensing data in attribution and modelling of floods.

2. Method

2.1. Study area

The selected catchments are located within and surrounding the urbanized towns of Swindon and Bracknell and include two national river flowing gauging stations used by the UK Environment Agency (EA) (National River Flow Archive stations 39052 and 39087) (Fig. 1). All catchments are tributaries within the Thames basin and have a similar climate, with the Standard Annual Average Rainfall (SAAR) of between 676 mm and 712 mm. Thames basin soils and geology are highly variable, but the selected catchments are generally similar, with shallow clay or loam soils, with neither dominated by groundwater inputs from Jurassic limestones. The similarity in soil hydrology, low slope, and overall topography was a basis for catchment selection (Miller & Hess, 2017). Alongside the two EA gauged catchments (herein labelled EA_39052 and EA_39087), data from a hydro-meteorological monitoring network spanning 16 variable urban catchments, of record length between 2 and 5 years between 2011 and 2016 (McGrane et al., 2017).Alongside the two EA gauged catchments (herein labelled EA_39052 and EA_39087), data from a hydro-meteorological monitoring network spanning 16 variable urban catchments, of record length between 2 and 5 years between 2011 and 2016 (McGrane et al., 2017) were additionally used (Fig. 1). These employed ultrasonic stream flow gauging technologies to monitor streamflow at high resolution and capture stormflow events and peak flows. These delineate a range of catchment types from rural to highly urbanized and contain a diversity of land cover and hydraulic infrastructure that influence the hydrological response (Miller & Hess, 2017).

Swindon has grown from a small 19th century industrial town into an area of mixed urbanized and peri-urban development and commerce with a population now exceeding 215,000 (2015). Bracknell was previously a small village but after being designated a new town in 1949 has grown rapidly to a population of 120,000 (2015). Bracknell was
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