

## **Refining flood estimation in urbanized catchments using landscape metrics**

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### **Highlights**

- Catchment descriptors compared with landscape metrics for estimation of urbanization effects on floods.
- Refined urbanized catchment descriptors calculated and compared to coarser national scale descriptors.
- Landscape metrics provide the ability to capture location, connectivity and patch size of urbanized areas.
- Flood estimation in urbanized catchments improved by using spatially explicit and hydrologically relevant landscape metrics.

**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.

**Keywords**

Hydrology; Urban; Flood; Landscape metrics; Catchment descriptors; Flood estimation

## 1 **1 Introduction**

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

10           In order to quantify the impacts of urbanization on the environment some form of  
11 classification or quantification of the urban fabric is required, for example, both the UK  
12 Countryside Survey (<http://www.countrysidesurvey.org.uk/>) and UK Flood Estimation  
13 Handbook (FEH) methods (Institute of Hydrology, 1999) rely upon a temporal range of UK wide  
14 Land Cover Mapping (LCM) products (Morton et al., 2011). Hydrological quantification of the  
15 urban environment can be derived from land use classes with variations based on density, for  
16 example, low-high density residential (Gallo et al., 2013) or using classes to derive an index of  
17 urbanization, for example, the catchment index of urban extent (*URBEXT*: Bayliss et al., 2006).  
18 These both provide an index of catchment imperviousness, or total impervious area (TIA), which  
19 is increasingly being directly measured using remotely sensed data to facilitate an enhanced  
20 representation of the urban environment (Weng, 2012), often for use in high-resolution  
21 hydrological modelling (Salvadore et al., 2015). Combining remote sensing imagery with other  
22 spatial data has proven particularly effective at determining how connected urban surfaces are to  
23 storm drainage, producing indicators such as directly connected impervious area (DCIA) (Roy

24 and Shuster, 2009) or effective impervious area (EIA) (Janke et al., 2011). However such detail  
25 is not always required at catchment scales (>0.25 ha) where TIA is sufficiently accurate for  
26 estimating DCIA across multiple developed parcels in certain applications (Roy and Shuster,  
27 2009) and URBEXT can be a direct index of imperviousness (Miller & Grebby, 2014). At  
28 national scales class based mapping remains more readily available and routinely used,  
29 particularly as it can offer historical picture of change. Progress is however being made across  
30 the globe in national mapping of imperviousness and temporal change, from Europe (EEA,  
31 2016) to India (Wang et al., 2017) and USA (US Geological Survey, 2013).

32 For national methods of flood estimation at ungauged sites, there remains in many  
33 countries a reliance on the simplicity of empirical formulae relating the index flood to catchment  
34 characteristics (Bocchilola et al., 2003) that include land class data to inform upon levels of  
35 imperviousness for more urbanized locations (Formetta et al., 2017). National agencies across  
36 Europe continue to employ such methods (Castellarin et al., 2012), based on regressions of index  
37 flood data to catchment characteristics in gauged basins. When considering more urbanized  
38 catchments, research has additionally highlighted the need to consider connectivity and location  
39 relative to the catchment outlet and scale considered (Kjeldsen et al., 2013; Miller et al., 2014;  
40 Sillanpää and Koivusalo, 2015). For example, in the UK, where such descriptors are routinely  
41 used to estimate the median annual flood (*QMED*), both Vesuviano et al (2016) and Faulkner et  
42 al. (2012) find that existing descriptors and equations perform with less certainty in small  
43 urbanized catchments compared to rural catchments. Further, Miller and Hess (2017) find a non-  
44 distributed measure such as imperviousness does not mirror the variation in peak flows between  
45 urban catchments potentially driven by spatial layout. Thus, while imperviousness is important,  
46 class data remain employed for its estimation, and as Mejía and Moglen (2009) show, it is

47 equally important to consider the spatial distribution of impervious land cover, as this can have  
48 consequences for the resulting flood peaks.

49         Spatial or landscape metrics are a tool for quantifying structure and pattern in thematic  
50 data, and have been highlighted by Herold et al. (2005) and Ogden et al. (2011) as valuable for  
51 improving representations of urban hydrological dynamics. The use of landscape metrics in  
52 hydrology has however been limited, despite showing promise in predicting urban land-use  
53 change impacts through representation of form and function (Lin et al., 2007; Van de Voorde et  
54 al., 2016). Comparatively, urban ecological research, which has long been using ecological  
55 typologies to study ecosystem dynamics (Brady et al., 1979), has evolved into many detailed  
56 landscape metrics of landscape structure in dedicated spatial statistical software (Kupfer, 2012)  
57 with diverse applications (e.g. Alberti, 2005; Jiao, 2015; Muhs et al., 2016). Within ecological  
58 landscape metrics, distance is often considered as Euclidean and thus is not calculated according  
59 to a hydrological network. The importance of hydrological distance to catchment outlet is  
60 demonstrated by Van Nieuwenhuysse et al. (2011), yet while aggregation based landscapes  
61 metrics have been tested for hydrological applications, and shown to be effective at providing an  
62 estimate for connectivity (Yang et al., 2011), there have been few efforts to consider  
63 hydrological distance. Wan Jaafar and Han (2012) have shown the potential for improving  
64 *QMED* using more hydrologically relevant descriptors to be derived from catchment form and  
65 information on land cover.

66         Local scale hydraulic features are increasingly being installed within the urban  
67 environment to control runoff, such as sustainable urban drainage systems (SuDS) (Woods  
68 Ballard et al., 2015). Studies suggest features such as green roofs (Vesuviano et al., 2014),  
69 offline storage (Wilkinson et al., 2010) and plot-scale bio-retention features (Hood et al., 2007)

70 reduce and attenuate runoff, but such features are not routinely mapped. Additionally,  
71 attenuation of runoff as baseflow (Rivett et al., 2011) can be altered by soil management  
72 (Holman et al., 2011) and evidence suggests that soils in urban areas can be so degraded through  
73 compaction and decreased hydraulic conductivity (Chen et al., 2014) that infiltration potential  
74 approaches that of impervious surfaces (Gregory et al., 2006) and increases runoff (Yang and  
75 Zhang, 2011). There are, however, currently no distinctions made in Land Cover Map (LCM)  
76 grassland classes between such surfaces (Morton et al., 2011). Conversely there is evidence that  
77 improving soil condition will improve infiltration (Chen et al., 2014) and better management of  
78 the urban landscape can provide green infrastructure (GI) and ecosystem services (Tratalos et al.,  
79 2007) that reduce runoff volumes (Shuster et al., 2014). Infiltration and local storage is also  
80 much improved in areas of preserved or managed nature and woodland (Nisbet and Thomas,  
81 2006). Again, given the potential role of SuDS and GI for flood attenuation, there is surprisingly  
82 little attention paid to mapping such land-use and testing its effect on urban runoff. There is  
83 however a growing body of research mapping GI, based on using remote sensing data (Liquete et  
84 al., 2015; Vatsava et al., 2016) and developing a comprehensive classification of GI (Koc et al.,  
85 2017). Given these recent advances, and recent GI interest in both the UK (Kelly, 2016; POST,  
86 2016) and internationally (Jarden et al., 2015), the lack of consideration regarding the  
87 functionality of SuDS and green space as GI, is clearly an area that should be expanded upon  
88 (Gill et al., 2007).

89         This study aims to use high-resolution spatial data alongside refined urban land cover  
90 classes from a UK case study to derive spatial landscape metrics and assess the potential  
91 application of landscape metrics for estimating the index flood in urbanized catchments. For this,  
92 three objectives are set: i) develop a set of hydrologically relevant urban land-use classes that can

93 be mapped using readily available geo-spatial information, ii) derive enhanced urbanized  
94 catchment descriptors and identify suitable landscape metrics for use in flood estimation within  
95 the United Kingdom, and iii) test the performance of updated catchment descriptors and  
96 landscape metrics for estimating *QMED* for selected study catchments compared with existing  
97 flood estimation methods. This will inform the potential for developing a wider method using  
98 spatial metrics and remote sensing data in attribution and modelling of floods.

## 99 **2 Method**

### 100 2.1 Study area

101 The selected catchments are located within and surrounding the urbanized towns of  
102 Swindon and Bracknell and include two national river flow gauging stations used by the UK  
103 Environment Agency (EA) (National River Flow Archive stations 39052 and 39087) (Figure 1).  
104 All catchments are tributaries within the Thames basin and have a similar climate, with the  
105 Standard Annual Average Rainfall (SAAR) of between 676mm and 712mm. Thames basin soils  
106 and geology are highly variable, but the selected catchments are generally similar, with shallow  
107 clay or loam soils, with neither dominated by groundwater inputs from Jurassic limestones. The  
108 similarity in soil hydrology, low slope, and overall topography was a basis for catchment  
109 selection (Miller & Hess, 2017). Alongside the two EA gauged catchments (herein labelled  
110 EA\_39052 and EA\_39087), data from a hydro-meteorological monitoring network spanning 16  
111 variable urban catchments, of record length between 2 and 5 years between 2011 and 2016  
112 (Miller et al., 2014; McGrane et al., 2016; Putro et al., 2016) were additionally used (Figure 1).  
113 These employed ultrasonic streamflow gauging technologies to monitor streamflow at high  
114 resolution and capture stormflow events and peak flows. These delineate a range of catchment

115 types from rural to highly urbanized and contain a diversity of land cover and hydraulic  
116 infrastructure that influence the hydrological response (Miller and Hess, 2017).

117 Swindon has grown from a small 19<sup>th</sup> century industrial town into an area of mixed  
118 urbanized and peri-urban development and commerce with a population now exceeding 215,000  
119 (2015). Bracknell was previously a small village but after being designated a new town in 1949  
120 has grown rapidly to a population of 120,000 (2015). Bracknell was designed with consideration  
121 of water management, utilizing a number of flood storage tanks and ponds within urbanized  
122 areas to attenuate floods and store sediment (Packman and Hewitt, 1998). Swindon has less flood  
123 storage infrastructure, but with increased development in recent years has had to adapt to  
124 increased flooding in certain dense areas of housing through flood protection measures.

## 125 **Figure 1**

### 126 2.2 Reclassification of land cover classes

127 The standard LCM groups of 50m gridded land cover classes used for flood estimation  
128 applications (Environment Agency, 2017) in urbanized areas of the UK (Table 1 - *Urban*;  
129 *Suburban*; *Water*; *Rural*: composed of Agricultural/managed and Woodland/scrub) were refined  
130 into more hydrologically relevant classes using a number of nationally available ancillary  
131 datasets (Table 1), illustrated in Figure 2. In order to identify key areas of ‘natural’ surfaces that  
132 might exist within the urban area and its fringes, relevant Natural England datasets were merged  
133 to provide a single dataset on natural areas.

## 134 **Table 1**

## 135 **Figure 2**



136           Reclassification of LCM classes, outlined in Table 2 and illustrated in Figure 2, was  
137 based on a hydrological perspective and consideration of features across the study areas that  
138 could significantly alter the rainfall-runoff response of catchments. The justification for the  
139 reclassifications and the additional SuDS sub-class, along with method used to map each  
140 typology, are outlined here:

141           *Urban*: Urban was not reclassified - agreeing with other studies assessing varying land  
142 use responses which have similarly used only one ‘Urban’ class, such as the ‘commercial’ class  
143 used by Gallo et al. (2013), and Van de Voorde et al. (2011) who reported classes of commercial  
144 and industrial areas had broadly similar levels of impervious cover (82% and 73%, respectively).

145           **Table 2**

146           *Suburban*: Suburban has been noted as a highly generalized class for hydrological  
147 applications (Kjeldsen et al., 2013; Miller et al., 2014) and the refined classification used in this  
148 study followed a classification according to density: low, medium and high, which has been  
149 shown to be effective in other studies (Sjöman and Gill, 2014; Gallo et al., 2013).

150           Reclassification of *Suburban* grids was undertaken using Ordnance Survey MasterMap (OSMM)  
151 (Appendix: Table 2).

152           *Water*: LCM areas of water were not found to cover many of the smaller and more  
153 fragmented water bodies evident in OSMM mapping in urban areas. Such features, despite their  
154 size, could play an active role in flood attenuation if receiving runoff from urban surfaces (Smith  
155 et al., 2013). The high level of water feature detail in OSMM mapping was used to develop a  
156 refined water raster and to identify any grids with a certain coverage of water features  
157 (Appendix: Table 3).

158           *Urban greenspace*: Greenspaces in urbanized areas have been shown to be  
159 hydrologically impacted compared to grassland and agriculture (Chen et al., 2014) with explicit  
160 effects evident as increases in runoff (Yang and Zhang, 2011). Existing approaches for semi-  
161 automated mapping of urban greenspace (e.g. Troy and Wilson, 2006; Gill et al., 2007; Vatsava  
162 et al., 2016) were not found to be suitable so patch size and location were utilized, whereby the  
163 size and location of the greenspace relative to urban areas were concurrently assessed  
164 (Appendix: Table 4), to isolate urban greenspaces (*Green<sub>URB</sub>*) such as recreation areas, roadside  
165 verges, and large gardens, from those larger, less altered, and more continuous areas of grassland  
166 and agriculture within or surrounding areas of development (*Green*) (Figure 2).

167           *Natural urban greenspace*: Natural areas of vegetation, either managed or conserved, can  
168 potentially reduce runoff (Gill et al., 2007), thus reducing the index flood. Natural areas of  
169 greenspace within or surrounding urban areas were classified as areas managed to preserve  
170 natural vegetation and soils, improving soil condition and permeability, leading to an enhanced  
171 capacity for abstraction and mitigation of runoff formation processes. These were identified from  
172 Natural England ancillary datasets (Table 1) and subsequently merged and gridded to a 50m  
173 scale to subsequently reclassify such areas (except water) as natural Greenspace (*Green<sub>NAT</sub>*)  
174 (Appendix: Table 5).

175           *SuDS*: An additional sub-class was added to the Urban and Suburban classes to account  
176 for the presence of localized SuDS designed to reduce runoff and frequent flooding (Defra,  
177 2014). The locations of SuDS were identified using a combination of geo-spatial information on  
178 age and suitability for SuDS (Appendix: Table 6). Age indicates developments designed and  
179 built after regulations required SuDS measures to be put in place (Flood and Water Management  
180 Act 2010). Sites built post 2000 were identified as having SuDS potential, here comparing all

181 Suburban and Urban surfaces in 2010 with 2000 (Miller and Grebby, 2014: Table 1). However,  
 182 as not all sites are suitable for SuDS, due to lack of soil infiltration or issues with groundwater,  
 183 the SuDS Infiltration Map (SIM: Dearden, 2016) was used to locate sites that should have SuDS  
 184 in place. Sites built post 2000 where SIM indicated SuDS suitability, were subsequently re-  
 185 classed as *SuDS*.

### 186 2.3 Identifying suitable catchment descriptors and landscape metrics

187 The second stage refined existing catchment descriptors using the refined land cover data, and  
 188 calculated and identified a number of potentially relevant landscape metrics. In the UK, the index  
 189 flood *QMED* is the flood exceeded in half of all years and forms the basis of subsequent  
 190 derivation of flood estimates for rarer events, such as the 1 in 100 year flood. *QMED* can be  
 191 accurately derived from hydrological observations of peak flows using the methods outlined in  
 192 volume 3 of the FEH (Institute of Hydrology, 1999: Chapter 12) – herein termed *QMED<sub>obs</sub>*. For  
 193 ungauged sites, *QMED* is estimated from a number of FEH catchment descriptors (Eq. 1) that are  
 194 derived from a regression between catchment descriptors and *QMED<sub>obs</sub>* (Kjeldsen, Jones and  
 195 Bayliss, 2008) – herein termed *QMED<sub>FEH</sub>*

$$\text{Eq. 1) } QMED_{FEH} = 8.3062 AREA^{0.851} 0.1536 \frac{1000}{SAAR} FARL^{3.4451} 0.0460 BFIHOST^2$$

196 In urban catchments, this is subsequently adjusted to account for the level of urbanization using  
 197 an Urban Adjustment Factor (UAF) based on the catchment urbanisation index *URBEXT* (Table  
 198 3).

#### 199 2.3.1 Catchment descriptors

200 The catchment descriptors used in the FEH statistical procedures for flood frequency estimation  
 201 were refined for use in this study, being calculated using the methods (Table 3) outlined by

202 Bayliss (1999) but with a higher resolution 10m DEM and the refined LCM classes (Table 2).

203 Here we outline the method and improvements gained over existing FEH descriptors used in Eq.

204 1.

205 *Catchment area – AREA*: Catchment areas were calculated using 10m resolution DEM data

206 (Table 1) in combination with storm drainage maps following the method of Rodriguez et al.

207 (2013) (Appendix: Table 3). The combination of DEM and drainage data is often necessary in

208 urban environments as artificial drainage can alter catchment area from natural conditions (Braud

209 et al., 2013). Finer scale resolution DEM data (5m) was not suitable as it captured manmade

210 interventions in the urban landscape that significantly altered the natural elevation surface and

211 thus drainage area, while lower resolution (50m) data did not capture small catchment areas and

212 was not suitable for the urban scale.

213 *Urban extent – URBEXT*: The index of urban extent provides a weighted index value for

214 Suburban and Urban land cover (Table 3) to provide a proxy measurement for imperviousness

215 within a catchment (Bayliss, 1999). This has been shown to be a robust method for estimating

216 imperviousness from land class data at catchment scales (Miller and Grebby, 2014). With the

217 refined Suburban classes (Table 2) the *URBEXT* calculation has been reclassified here

218 ( $URBEXT_{rc}$ ) using weightings (Eq. 2) that account for the variation in impervious/pervious

219 surfaces between the new classes. Additionally, *Urban* or *Suburban* class areas re-classified as

220 *SuDS* were not included in this revised calculation, as SuDS are designed to effectively remove

221 the hydrological impact of impervious surfaces for all but extreme events (POST, 2007; Ballard

222 et al., 2015; Environment Agency, 2013).

Eq. 2) 
$$URBEXT_{rc} = URBAN + 0.75 SUBURBAN_{HD} + 0.5 SUBURBAN_{MD} + 0.25 SUBURBAN_{LD}$$

223

224 *Flood attenuation – FARL*: The method used to calculate an index of attenuation from rivers and  
 225 lakes - *FARL* - follows the FEH method outlined by Bayliss (1999: Table 3). The basis of this  
 226 method is that the storage of high flows in lakes and reservoirs will attenuate the flood  
 227 hydrograph, and that large lakes with large drainage areas have a high storage potential, and can  
 228 modify flood response to a greater extent than small lakes with small drainage areas. Bayliss  
 229 (1999) utilized a 50m gridded reservoir/lakes dataset developed as part of the Institute of  
 230 Hydrology Digital Terrain Model (IHDTM) which was found to be broadly similar to the lakes  
 231 and reservoirs mapped in the LCM data and OS 1:50,000 Landranger map series (Morris and  
 232 Flavin, 1990). Here, we recalculate a refined flood attenuation index  $FARL_{rc}$  using the refined  
 233 Water class detailed in 2.2 that captures much smaller local water bodies in urbanized areas.

234 *Catchment slope and drainage path length – DPSBAR and DPLBAR*: Mean catchment slope and  
 235 mean drainage path length were calculated using the methods outlined by Bayliss (1999: Table  
 236 3) but using the 10m DEM and associated flow accumulation network utilized in this study. This  
 237 is more accurate in urban areas, capturing artificial drainage and associated alterations to natural  
 238 pathways.

239 *Hydrological soil type – BFIHOST*: Soil hydrology type is defined by the base flow index  
 240 (*BFI*) for the dominant hydrology of soil type (*HOST*) class (Boorman et al., 1995) within each  
 241 catchment (*BFIHOST*).

242 2.3.2 Landscape metrics for connectivity and location

243 Landscape metrics suitable for connectivity representation were selected and calculated  
 244 using the FRAGSTATS software (McGarigal and Marks, 1994). Both the class-based and  
 245 landscape metrics selected are detailed in Table 3, along with details on the calculation method,  
 246 parameters, and source.

247 **Table 3**

248 While landscape metrics used in ecological applications have shown some effectiveness  
 249 for attributing hydrological response through measuring general shape (Lin et al., 2007), other  
 250 metrics using hydrological distance, rather than Euclidian distance, have been shown to be more  
 251 effective at representing hydrological connectivity. Van Nieuwenhuysen et al. (2011) found that  
 252 landscape metrics can be particularly useful for expressing connectivity of hydrological systems,  
 253 and that hydrological connectivity is determined by the spatial organisation of heterogeneity.  
 254 They took the Proximity Index ( $PX$ ) metric developed by Gustafson and Parker (1992) to  
 255 account for Euclidean distance and connectivity and adapted this to capture the effects of both  
 256 hydrological distance and connectivity of urbanized patches to the catchment outlet (Eq. 3):

Eq. 3) 
$$PX = \sum A_k / mdo_k$$

257 where,  $A_k$  is the area of patch  $k$ , and  $mdo_k$  is the mean distance to the outlet ( $mdo$ : Table 3) of  
 258 patch  $k$ , and  $PX$  is the product of these ratios for all *Urban* and *Suburban* land use patches.

259 While the  $PX$  metric used by Van Nieuwenhuysen et al. (2011) did incorporate  
 260 hydrological distance, the application was for a stochastic drainage network within a triangular  
 261 conceptual catchment. Thus we have additionally normalized both patch area  $A_k$  and patch flow

262 path length  $d_k$  by catchment area ( $AREA$ ) and mean catchment drainage path length ( $DPLBAR$ ),  
 263 respectively, to additionally derive a normalized unit-less  $PX_N$  index (Eq. 4);

Eq. 4)

$$PX_N = \sum \frac{A_k/AREA}{mdo_k/DPLBAR}$$

264 In total, 30 separate landscape and class-based metrics were computed (Appendix: Table  
 265 8) by using the metrics in Table 3 and in Eqs 2-4 across the variable classes considered. This  
 266 included 10 *Urban* and 10 *Suburban* class metrics, 3 landscape metrics, 5 hydrological metrics,  
 267 and 2 *Green<sub>NAT</sub>* class metrics. To determine which catchment descriptors (2.3.1) and potentially  
 268 suitable landscape metrics (2.3.2: Table 3; Appendix Table 8) should be used in the development  
 269 of a revised index flood equation ( $QMED_{rev}$ ), we assessed correlations between  
 270 descriptors/metrics against the observed index flood  $QMED_{obs}$  using Spearman's rank correlation  
 271 coefficient (Spearman, 1904).  $QMED_{obs}$  was calculated for each catchment from the monitored  
 272 data using the methods outlined in FEH (Institute of Hydrology, 1999).

273 Catchment descriptors are routinely used for deriving flood estimates for ungauged  
 274 catchments based on derived relationships between peak flows and various catchment descriptors  
 275 in both the UK (Environment Agency, 2012) and internationally (Feaster et al., 2014). The third  
 276 stage introduced the refined descriptors and metrics into a regression model for estimating the  
 277 index flood ( $QMED$ ) for the selected catchments to assess the potential for using landscape  
 278 metrics in flood estimation. Here this was done using three steps: i) identifying the best  
 279 performing variables in a step-wise regression against  $QMED_{obs}$ ; ii) deriving  $QMED_{rev}$  for all  
 280 sites using the regression variables, and; iii) comparing the performance of  $QMED_{rev}$  and  
 281  $QMED_{FEH}$  against  $QMED_{obs}$  for all sites.

282 *QMED* was derived for the 18 sites across both study sites using both the observation-  
283 based (*QMED<sub>obs</sub>*) and catchment descriptor-based (*QMED<sub>FEH</sub>*) methods to provide baseline  
284 estimates with which to compare the performance of the refined catchment descriptor equation  
285 (*QMED<sub>rev</sub>*) that utilizes the refined descriptors and landscape metrics (Section 2.3). In order to  
286 identify the best performing descriptors/metrics as variables for *QMED<sub>rev</sub>* we employed the  
287 weighted least squares (WLS) approach to linear regression modelling (Ruppert and Wand,  
288 1994). The WLS approach was the most suitable regression given that the limited number of  
289 catchments and limited quantity of annual maxima at 16 of the 18 sites precluded accounting for  
290 covariance in estimating *QMED*. The WLS approach involved iterative testing of potential  
291 variables for estimating *QMED* and applying a weighting factor based on record length. For each  
292 iteration all metrics were compared using the following transformations: none, logarithmic,  
293 inverse (1000/x), and power ( $c^x$ ) and the best performing combination of metrics was retained  
294 based on the adjusted  $r^2$ .

### 295 **3 Results and discussion**

#### 296 **3.1 Refining urban land cover classes**

297 Mapping of the refined urban land use classes (Table 2) formed the first step in deriving  
298 enhanced catchment descriptors and landscape metrics. The results of refining the existing basic  
299 LCM classes for Swindon and Bracknell are illustrated in Figure 3 and summarized in Table 4.

#### 300 **Figure 3**

#### 301 **Table 4**

302 The most evident and expected change observed in Figure 3 between the standard and refined  
303 classification is the significant change in the Suburban class. Table 4 reveals the majority



304 becomes reclassified as either low-density Suburban<sub>LD</sub> (peripheral, isolated, satellite or rural)  
305 developments or medium-density Suburban<sub>MD</sub> (cores of large suburban) developments. A much  
306 lower portion becomes reclassified as high-density Suburban<sub>HD</sub> areas close to central urban  
307 development. This suggests that impervious cover, relative to development density, may be  
308 overestimated when using a less detailed index of urban extent such as *URBEXT* or taking an  
309 assumed impervious cover and applying it to a single urban land use class that is in reality highly  
310 variable, as identified by Redfern et al. (2016). Additionally, the form this takes differs between  
311 the two catchments, mainly due to historical development patterns. The higher relative coverage  
312 of low-density development in Bracknell (Table 4) further indicating variability in impervious  
313 cover not well represented by a single suburban class applied over a range of different catchment  
314 development types. Further, while Miller and Grebby (2014) found that *URBEXT* was indicative  
315 of impervious cover in small urban catchments, that study only considered a limited area with  
316 very similar development types. This points to the potential for significantly improving estimates  
317 of urbanisation impacts in catchment descriptor-based flood estimation methods for urbanized  
318 catchments by directly using impervious estimates derived from remote sensing imagery (Weng,  
319 2012).

320         The high proportion of low-density suburban housing identified in this study poses  
321 significant potential for contributing large areas of domestic garden as green infrastructure  
322 (Cameron et al., 2012), which have been shown to have a role in runoff regulation (Warhurst et  
323 al., 2014). Such variability could be important for explaining the fact that generalized estimates  
324 of impervious cover based on *URBEXT* do not explain hydrological response in urbanized  
325 catchments (Miller and Hess, 2017). Further, while impervious estimates may be ultimately  
326 refined, the refined classes based on density may in fact offer additional information on the

327 variability of water management and transfer, and therefore GI potential, not quantified by  
328 imperviousness alone.

329 In both catchments the Water class in standard LCM mapping is not high (0.1-0.3%:  
330 Table 4), however the inclusion of OSMM water has significantly increased water cover in both  
331 catchments, by 400% in Swindon, and nearly 300% in Bracknell. Although the relative areas are  
332 not high compared to total catchment area (0.5% and 1.1% for Swindon and Bracknell,  
333 respectively), it must be considered that it is the area serviced by these water bodies that's  
334 important (*FARL* – Table 3) and thus these changes should affect *FARL*. Additionally much of  
335 this increased cover is within urban areas, so could be providing localized flood attenuation, with  
336 the higher value in Bracknell reflecting the deliberate design of flood attenuation features  
337 (Packman and Hewitt, 1998). The availability of high resolution OSMM data provides the user  
338 with up to date and accurate data from which to delineate such features. Given that new small  
339 waterbodies are increasingly being used in mitigating runoff in urban catchments (Jarden et al.,  
340 2015; Wilkinson et al., 2010) these results highlight the importance of using contemporary high-  
341 resolution imagery to map such features. One shortcoming however is that such methods do not  
342 facilitate identification of temporary storage features, such as swales or offline temporary  
343 storage. Subsurface retention areas are also not identified. Both have been identified as having  
344 flood storage capacity (CIRIA, 2014) but would be difficult to map from remote imagery.

345 The overall coverage of completely pervious classes (Grassland/Agriculture, Woodland)  
346 between the two towns and surrounding catchment is a combined 60.3% in Swindon, and 59.3%  
347 in Bracknell (Table 4), reflecting the urbanized nature of both catchments. The distribution  
348 within classes is different however, reflective of geographical location and planning controls:  
349 Bracknell being located near to London but having a large area of protected woodland to the

350 south, and Swindon being more remote and surrounded by farmland. Urban reclassification of  
351 greenspaces indicates that urban greenspace (*Green<sub>URB</sub>*) can make up significant areas within the  
352 urban fringes (2.3 – 4.4%). While less than 10% of overall pervious cover (31.1-49.3%), if such  
353 areas are fundamentally so altered or compacted as to behave like impervious surfaces (Chen et  
354 al., 2014) then the effect on runoff within the urban areas is likely to be significant at local  
355 scales. These effects could however be balanced by the areas of natural greenspace (*Green<sub>NAT</sub>*)  
356 that have been shown to reduce runoff through enhanced infiltration (Zhang et al., 2015).  
357 Certainly such areas could play a role in localized runoff reduction, and given their location in  
358 these towns, this reveals the importance of considering types of urban greenspace and of using  
359 high accuracy datasets for estimating local runoff in urban areas (Verbeiren et al., 2013).

360 Further refinement by identification of likely areas of SuDS did not reveal any significant  
361 areas, with total areas of 0.3% and 0.4% in Swindon and Bracknell, respectively (Table 4). These  
362 are likely to be conservative values, reflecting that while much of Swindon is not hydro-  
363 geologically suitable for infiltration based SuDS, being composed of clay soils, retention based  
364 SuDS could be prevalent. Similarly, in Bracknell retention SuDS design is in fact integrated into  
365 the overall hydraulic design of the town, rather than having localized implementation or  
366 infiltration-based measures. Even so, the low values do not indicate these sub-classes will have a  
367 significant impact on refining *URBEXT* or explaining *QMED* in this study. However, with new  
368 developments required to implement such features where possible (Defra, 2011), such areas will  
369 increasingly become important. Going forward, accurately delineating areas serviced by SuDS is

370 a clear priority for urban land cover mapping. This will enable better modelling of SuDS impacts  
 371 and more accurate representation in a suitable catchment scale index for index flood methods.

### 372 3.2 Identifying suitable catchment descriptors and landscape metrics

373 A comparison between FEH catchment descriptors and those derived from refined classes  
 374 across the 18 sites revealed there to be a high degree of correlation ( $>0.95$ ), with associated  
 375 minor improvements ( $<0.05$ ) to the correlations with  $QMED_{obs}$  for all except  $FARL_{rc}$  ( $-0.22 \rightarrow -$   
 376  $0.38$ ) which improved significantly. Regression model analysis (Table 5) further indicated the  
 377 significant relationships between both standard and reclassified descriptors across the 18 sites,  
 378 with the lowest fit observed for  $FARL_{rc}$  ( $r^2 = 0.894$ ) while both  $AREA_{rc}$  and  $URBEXT_{rc}$  exceed an  
 379  $r^2$  of 0.99. Taken together these results suggest the use of the reclassified  $FARL_{rc}$  catchment  
 380 descriptor will improve estimates of catchment flood attenuation from water bodies in small  
 381 urbanized catchments, and subsequently replaces  $FARL$  in this study.

### 382 **Table 5**

383 For  $URBEXT_{rc}$  the correlation with  $QMED_{obs}$  actually decreased ( $-0.05$ ), indicating that  
 384 the refined suburban classes and inclusion of SuDS areas provides no evident improvement in  
 385 providing a descriptor of urban extent for use in  $QMED$  estimation across the 18 sites. Combined  
 386 with the high model  $r^2$  in Table 5 this further suggests that detailed efforts to map variation in  
 387 suburban land cover classes under current conditions has no real benefit for estimating  $QMED$ ,  
 388 and as such we retained the standard  $URBEXT$  and Urban/Suburban land cover classes for  
 389 subsequent steps. Other studies have shown that such variation only becomes important at local  
 390 scales (Shuster et al., 2005) or between distinct development types (Valtanen et al., 2013). Going  
 391 forward however, as SuDS are increasingly adopted and more attention is paid to urban design to  
 392 reduce runoff generation, such a refined approach could well become much more important.

393  $AREA_{rc}$  showed minor improvements over standard values but importantly did not  
394 consider those four small urban catchments (S4, S7, S9, S10) in which it was not possible to  
395 automatically determine catchment area, as no natural catchment existed at these artificial  
396 drainage points. This is a limiting factor in using FEH catchment descriptors for small highly  
397 altered urban catchments (Miller et al., 2014). This highlights the need for a high resolution  
398 DEM to be used in conjunction with ancillary datasets on stormwater infrastructure and  
399 impervious areas to delineate artificial urban catchment boundaries (Braud et al., 2013).  $AREA_{rc}$   
400 values were used henceforth in place of  $AREA$ .

401 From the 30 catchment descriptors and landscape metrics computed (Appendix: Table 8),  
402 this was reduced down in four iterations to 17 descriptors/metrics (Table 6) that are subsequently  
403 used. This includes 12 landscape metrics that were not significantly ( $>0.8$ ) correlated with at  
404 least three other metrics, alongside four catchment descriptors used in estimating  $QMED$  (Eq. 1)  
405 and one ( $URBEXT$ ) used to adjust for urbanization (Kjeldsen, Jones and Bayliss, 2008). Table 6  
406 reveals that  $AREA_{rc}$ , as expected, was the most highly correlated descriptor to  $QMED_{obs}$  (0.95).  
407 For the landscape metrics,  $PX$  correlates surprisingly well with  $QMED_{obs}$  (0.82), as does  
408  $COHESION_{URB}$  (0.61). Interestingly, many of the metrics applied to Urban or Suburban classes  
409 prove more correlated with  $QMED_{obs}$  than  $URBEXT$ . Additionally, the normalised  $PX_N$  does not  
410 correlate as well with  $QMED_{obs}$  (-0.52), but performs better than  $URBEXT$  (-0.36) with which it  
411 is highly correlated (0.83). This suggests that efforts to normalize the  $PX$  metric reduces its  
412 descriptive ability and renders it more like  $URBEXT$ , further illustrating the relatively weak  
413 performance of this catchment descriptor at such local urban scales compared to more spatially  
414 orientated landscape metrics. The results detailed in Table 6 suggest that some metrics could be  
415 important variables in the final  $QMED$  regression, thus reinforcing what Van Nieuwenhuysse et

416 al. (2011) and others have found (e.g. Lin et al. 2007; Yuan et al. 2015) in that landscape metrics  
 417 are a useful tool for comparing hydrological basins with significant potential for application in  
 418 lumped hydrological studies and modelling.

419 **Table 6**

420 3.3 Catchment descriptors and landscape metrics for flood estimation

421 The optimal configuration for refining the  $QMED$  equation was to follow the FEH  
 422  $QMED_{FEH}$  equation (Eq. 1) and iteratively select four catchment descriptors and/or landscape  
 423 metrics as variables based on forward step-wise maximisation of the adjusted  $r^2$  using the  
 424 weighted least squares (WLS) function (Ruppert and Wand, 1994) against  $QMED_{obs}$  for the 18  
 425 sites. The four variables identified were catchment areas ( $AREA_{rc}$ ), and three landscape metrics:  
 426  $PX$ ,  $COHESION_{SUB}$ , and  $CONTAG$ .

427 The final derived equation of the maximised WLS regression for  $QMED_{rev}$  across the 18  
 428 sites using the variables selected is shown in Eq.5. Table 7 details the catchment values for the  
 429 selected variables along with the model fit and differences in estimated index flood values for  
 430 both  $QMED_{rev}$  and  $QMED_{FEH}$  compared with  $QMED_{obs}$  (catchment FARL and URBEXT values  
 431 are also included for reference). Importantly, the addition of  $PX$  proved highly effective at  
 432 explaining the variability in  $QMED_{obs}$  not covered by  $AREA_{rc}$  alone from an adjusted  $r^2$  of 0.848  
 433 to 0.972, and the inclusion of the final two metrics only improved the overall fit to  $r^2=0.984$ . The  
 434 range of values for both these additional metrics is generally low across the sites but a very high  
 435  $CONTAG$  value at S10 (93.8: Table 7) and low  $COHESION_{SUB}$  value for S2 (81.4: Table 7)  
 436 could explain their inclusion in the final equation, given both sites have the same  $QMED_{obs}$  (0.64  
 437  $m^3s^{-1}$ : Table 7) but are significantly different in area (S2 - 3.24  $km^2$ ; S10 - 0.49  $km^2$ ). The high  
 438  $CONTAG$  value at S10 is indicative of the fact that the area is almost entirely Suburban and has

439 high storm drainage connectivity, while the low  $COHESION_{SUB}$  value at S2 is clearly indicative  
 440 of a rural catchment with patchy areas of housing and low drainage connectivity.

$$\text{Eq. 5)} \quad QMED_{rev} = 357.0943 \text{ AREA}_{rc}^{0.4007} \text{ PX}^{0.8195} 1.0595^{COHESION_{SUB}} 1.0115^{CONTAG}$$

441

#### 442 **Table 7**

443 Overall  $QMED_{rev}$  was shown to have an  $r^2$  of 0.984 across the 18 sites, an improvement  
 444 over the  $r^2$  of 0.907 estimated by using  $QMED_{FEH}$ . Assessing the performance across the 18 sites  
 445 and between each method for estimating  $QMED$  it is clear from Table 7 that  $QMED_{rev}$  performs  
 446 well against the observed values, with an average difference of only -3.5%, and exceeding 25%  
 447 in only two cases (B5 and B6) where it significantly underestimates  $QMED$ . The FEH equation  
 448 performed well considering these are small highly-urban catchments and the  $QMED_{FEH}$  is  
 449 derived from national data across a wide range of catchment types and scales, but still had a  
 450 mean difference to  $QMED_{obs}$  of -27.5% and a majority of sites (12) exceeding 25%. There are no  
 451 discernible patterns to explain why certain catchments performed better or worse, either relative  
 452 to size or potential flood attenuation ( $AREA_{rc}$  and  $FARL_{rc}$ : Table 7), level of urbanization  
 453 ( $URBEXT$ ), location (Swindon or Bracknell), monitoring source (EA gauging or local  
 454 monitoring) or between methods. This would indicate that the revised equation based on  
 455 landscape metrics performs well across a range of catchments from predominantly rural, e.g. B1  
 456 and S2, to highly urbanized e.g. S9 and B3.

457 While  $FARL_{rc}$  was not included in the step-wise variable selection it should be noted that  
 458 it may well pose a greater significance across a broader selection of study catchments as in  
 459 certain Bracknell catchments (B1, B5, B6, EA\_39052: Table 7).  $FARL_{rc}$  falls below the threshold

460 value 0.9 below which the EA do not recommend using the catchment descriptor method for  
461 estimating *QMED* (Environment Agency, 2012). This demonstrates the value of using high-  
462 resolution imagery for identifying such small but potentially hydrologically important features.

463         Considering urbanization, the lack of a significant relationship between *URBEXT* and  
464 *QMED<sub>obs</sub>* ( $r^2=0.09$ ) compared to the stronger relationship with *PX* ( $r^2=0.634$ ), would indicate that  
465 urbanization is not a good indicator of high flow variability in urbanized catchments without  
466 explicit consideration of spatial layout. This unexpected pattern was similarly observed by Miller  
467 and Hess (2017) and highlights the value of considering both the relative coverage and  
468 hydrological distance to outlet of each urban patch. This study demonstrates that such a  
469 landscape metric could improve flood estimation in urban catchments and should be considered  
470 at a more national scale in flood estimation, particularly in the light of growing urbanization, and  
471 poor performance of existing methods in small urban catchments (Faulkner et al., 2012). Further,  
472 both *TIA* and distribution of impervious area, will certainly be improved by using detailed  
473 mapping of imperviousness from remote sensing imagery, as shown in numerous detailed  
474 hydrological studies (Dams et al., 2013; Verbeiren et al., 2013). Further, the inclusion of both the  
475 class-based *COHESION* metric applied to suburban areas and the landscape-based *CONTAG*  
476 metric, demonstrates that such metrics could be useful at capturing variability in between  
477 catchments not covered by explicit representation of area or urbanisation.

478         The omission of both variables *FARL* and *URBEXT* from the revised index flood  
479 equation *QMED<sub>rc</sub>*, and the performance of landscape metrics compared to such routinely used  
480 descriptors, was surprising and indicates such metrics, could have significant potential in  
481 improving flood estimates in ungauged small urban catchments. Similarly, other studies have  
482 shown that alternative catchment descriptors can be derived from readily available geo-spatial



483 data, and prove both more heterogeneous and perform better at estimating *QMED* (Wan Jaafar  
484 and Han, 2012). Overall, this study has demonstrated the potential of ecological landscape  
485 metrics (Yang et al., 2011) and hydrologically relevant metrics (Van Nieuwenhuysen et al., 2011)  
486 for estimating *QMED* in urbanized catchments.

#### 487 **4 Conclusions**

488 This study has sought to assess the potential for refined land cover information and  
489 landscape metrics in flood estimation. The results of refining catchment descriptors using higher-  
490 resolution data suggest that using such data alongside emerging datasets can alter the  
491 representation of the urban environment, having particular impacts on how urban water features  
492 are accounted for and where the catchment boundaries exist. Additionally, they suggest that class  
493 based approaches can be limited by nationally available data, indicating the need to test the  
494 application of more detailed global remotely sensed data. The results of employing landscape  
495 metrics alongside catchment descriptors has shown that index flood estimation in urbanized  
496 catchments could be improved by employing landscape metrics that represent hydrological  
497 distance relative to patch size and connectivity of urbanized areas. These provide a means of  
498 representing the hydrological complexity of an urban catchment in a single but spatially-explicit  
499 distributed numeric form, suitable for design flood methods and lumped hydrological modelling.  
500 We conclude the evidence indicates that a ‘one-size-fits-all’ national approach to flood  
501 estimation in urbanized areas could be improved by having more spatially explicit catchment  
502 descriptors and *QMED* equations, and that this should be the focus of further research to upscale  
503 and validate the application of such metrics and refined index flood equations.

504 The ability of landscape metrics to express hydrological connectivity and relative size  
505 and location of urban development to the location of interest has been clearly shown and

506 promises significant urban planning improvements for flood management. This suggests such  
507 metrics could further be useful in the design and testing of green infrastructure for natural flood  
508 management, given their respective role in mitigation of floods and clear links between runoff  
509 and catchment properties.

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728 **5 Tables**729 *Table 1: Source geo-spatial data and derived geo-spatial data*

<b>Dataset</b>	<b>Data type</b>	<b>Description</b>
OS Master Map Topography Layer	Polygon	OS MasterMap Topography Layer is a large-scale digital database of detailed surface features in the landscape of Great Britain.  ( <a href="http://www.ordnancesurvey.co.uk">www.ordnancesurvey.co.uk</a> )
Land Cover Map (LCM) (2015)	Raster (50m)	LCM is a national mapping product derived from satellite images and digital cartography and gives land cover information for the entire UK. LCM used in this study is an updated version of the most recent national dataset LCM 2007 (Morton et al., 2011)
Natural Areas	Polygon	Mapping of Local Nature Reserves, Country Parks, and Woodpasture and Parkland sites – from Natural England.  <a href="http://magic.defra.gov.uk/">http://magic.defra.gov.uk/</a>
SuDS Infiltration Map	Polygon	Mapping of SuDS potential – based on derived substrate infiltration properties. (Dearden, 2016)
Urban/Suburban Land Use Change (1960 – 2010)	Raster (50m) aggregated from 1m raster	Mapping of Urban and Suburban LCM classes using historical topographical mapping (1960 – 2010) published by Ordnance Survey.
NEXTMap Digital Elevation Model (DEM)	10m DEM	Used to determine surface-water catchment boundaries and flow pathways/accumulation.

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733 Table 2: Refined Land Cover Mapping urban hydro-typologies. Suburban sub-classes were based on typical development density  
734 ranges (Appendix: Table 1) for 9 selected training areas selected from visual analysis of aerial photography.

LCM classes	Refined typology	Sub-class (SuDS)	Description
Urban	Urban	Urban <sub>SUDS</sub>	Town centre/ industry/commercial/office/large infrastructure
Suburban	Suburban <sub>HD</sub> (High-Density)	Suburban <sub>SUDS</sub>	High-density building (> 19% per 50 x 50m <sup>2</sup> grid) e.g. urban fringe and terraced
	Suburban <sub>MD</sub> (Medium-Density)	Suburban <sub>SUDS</sub>	Medium density building (13% - 19% per 50 x 50m <sup>2</sup> grid) e.g. peri- urban housing developments
	Suburban <sub>LD</sub> (Low-Density)	Suburban <sub>SUDS</sub>	Low density building (<13% per 50 x 50m <sup>2</sup> grid) e.g. rural and isolated developments
Woodland	Woodland		Areas of continuous woodland and shrub
Agricultural/ managed	Greenspace (Green)		Land with agricultural or managed land use not in an urban area
	Greenspace – urban (Green <sub>URB</sub> )		Highly managed green space within urban areas (e.g. parks, recreation areas)
	Greenspace – natural (Green <sub>NAT</sub> )		Natural/ low-management greenspaces such as nature reserves and conservation woodland
Water	Lake/Pond/Wetland		Natural water body identified on LCM and with additional water bodies from OSMM

736 Table 3: FEH catchment descriptors used for estimating QMED and selected hydrologically suitable landscape metrics

Descriptor/ Metric	Formula	Explanation	Parameters
<b>FEH catchment descriptors</b>			
<b>Area</b>		Catchment drainage area (km <sup>2</sup> )	A = Area of catchment
<b>SAAR</b>	$\frac{\sum_{i=1961}^{1990} P_i}{30}$	Standard-period Average Annual Rainfall (mm) rainfall for the period 1961-1990 in Great Britain and Northern Ireland	P = Precipitation (annual total)
<b>FARL</b>	$FARL = \prod_{i \in \epsilon} \alpha_i$ <p>where:</p> $\alpha = (1 - \sqrt{r})^w$ $r = \frac{\text{water surface area}}{\text{subcatchment area}}$ $w = \frac{\text{subcatchment area}}{\text{catchment area}}$	Index of flood attenuation from rivers and lakes. The overall FARL index has a value close to one when a catchment has low attenuation from water bodies, and as attenuation effects become more important the index decreases.	$\alpha$ = effect of individual water body $r$ = relative size of water body to upstream catchment $w$ = weighting reflecting importance of water body
<b>BFIHOST</b>	Area weighted base flow index (BFI) assigned from catchment 1km gridded dominant HOST class	Base flow index from Hydrology of Soil Types (HOST) Boorman et al. (1995)	
<b>URBEXT</b>	$URBEXT = Urban + 0.5 Suburban$	FEH index of fractional urban extent	Urban and Suburban are Land Cover Mapping (LCM) classes for urbanized surfaces
<b>Class based landscape metrics</b>			

<b>Percentage of Landscape</b>	$PLAND = A_C/A_T$	Equals the percentage of the landscape comprised of the corresponding patch type.	$A_C$ = Class area $A_T$ = Total catchment area
<b>Perimeter-Area Ratio</b>	$PARA = \frac{P_{ij}}{a_{ij}}$	<i>Perimeter-area ratio</i> is a simple measure of shape complexity, but without standardization to a simple Euclidean shape	$p_{ij}$ = perimeter (m) of patch ij. $a_{ij}$ = area (m <sup>2</sup> ) of patch ij.
<b>Total Edge</b>	$TE = \sum_{k=1}^m e_{ik}$	<i>Total edge</i> at the class level is an absolute measure of total edge length of a particular patch type.	$e_{ik}$ = total length (m) of edge in landscape involving patch type (class) i; includes landscape boundary and background segments involving patch type i.
<b>Edge Density</b>	$ED = \frac{E}{A} (10,000)$	<i>Edge density</i> reports edge length on a per unit area basis that facilitates comparison among landscapes of varying size	$E$ = total length (m) of edge in the landscape. $A$ = total landscape area (m <sup>2</sup> ).
<b>Contiguity Index</b>	$CONTIG = \frac{\left[ \frac{\sum_{r=1}^z c_{ijr}}{a_{ij}} \right]}{v - 1}$	Assesses the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index of patch boundary configuration and thus patch shape	$c_{ijr}$ = contiguity value for pixel r in patch ij. $V$ = sum of the values in a 3-by-3 cell template (13 in this case). $A_{ij}$ = area of patch ij in terms of number of cells.
<b>Largest Patch Index</b>	$LPI = \frac{\max(a_{ij})}{A} (100)$	<i>Largest patch index</i> at the class level quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.	$a_{ij}$ = area (m <sup>2</sup> ) of patch ij. $A$ = total landscape area (m <sup>2</sup> ).



<b>Clumpiness index</b>	<p>Given:</p> $G_i = \left( \frac{g_{ii}}{\sum_{i=1}^m g_{ii}} - \min e_i \right)$ $CLUMPY = \left[ \frac{G_i - P_i}{P_i} \text{ for } G_i < P_i \& P_i < 5, e; \text{ else } \frac{G_i - P_i}{1 - P_i} \right]$	<p>The proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution.</p>	<p><math>g_{ii}</math> = number of like adjacencies (joins) between pixels of patch type (class) I based on the <i>double-count</i> method.</p> <p><math>G_{ik}</math> = number of adjacencies (joins) between pixels of patch types (classes) I and k based on the <i>double-count</i> method.</p> <p>Min-<math>e_i</math> = minimum perimeter (in number of cell surfaces) of patch type (class) I for a maximally clumped class.</p> <p><math>P_i</math> = proportion of the landscape occupied by patch type (class) i.</p>
<b>Cohesion</b>	$COHESION = \left[ 1 - \frac{\sum_{j=1}^n p_{ij}}{\sum_{j=1}^n p_{ij} \sqrt{a_{ij}}} \right] \left[ 1 - \frac{1}{\sqrt{A}} \right]^{-1} (100)$	<p><i>Patch cohesion index</i> measures the physical connectedness of the corresponding patch type.</p>	<p><math>p_{ij}</math> = perimeter of patch ij in terms of number of cell surfaces</p> <p><math>a_{ij}</math> = area of patch ij in terms of number of cells.</p> <p>A = total number of cells in the landscape.</p>
<b>Landscape metrics</b>			
<b>Contagion Index</b>	$CONTAG = 1 + \sum \sum [q_{ij} \ln(q_{ij})] / 2 \ln(2)$	<p>Assesses the extent to which patch types are aggregated or clumped as a percentage of the maximum possible; characterized by high dispersion and interspersion.</p>	<p><math>P_i</math> = proportion of the landscape occupied by patch type (class) i.</p> <p><math>g_{ik}</math> = number of adjacencies (joins) between pixels of patch types (classes) i and k based on the <i>double-count</i> method.</p> <p>m = number of patch types (classes) present in the landscape, including the landscape border if present.</p>
<b>Landscape Shape Index</b>	$LSI = \frac{e_i}{\min e_i}$	<p><i>Landscape shape index</i> provides a simple measure of class aggregation</p>	<p><math>e_i</math> = total length of edge (or perimeter) of class i in terms of number of cell surfaces;</p>

		or clumpiness and, as such, is very similar to the aggregation index.	includes all landscape boundary and background edge segments class i.  min $e_i$ = minimum total length of edge (or perimeter) of class i in terms of number of cell surfaces
<b>Effective Mesh Size</b>	$MESH \frac{\sum_{j=1}^n a_{ij}^2}{A} \left( \frac{1}{10000} \right)$	MESH provides a relative measure of patch structure	$a_{ij}$ = area (m <sup>2</sup> ) of patch ij.  A = total landscape area (m <sup>2</sup> ).

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739 *Table 4: Percentage coverage of standard and reclassified (rc) Land Cover mapping (LCM) classes, with distribution by*  
 740 *catchment, and overall areas of Suburban and Urban areas serviced by Sustainable Urban Drainage Systems (SuDS).*

LCM classes	LCM <sub>rc</sub> classes	Swindon			Bracknell		
		LCM	LCM <sub>rc</sub>	SuDS	LCM	LCM <sub>rc</sub>	SuDS
Urban	Urban	12.9%	12.8%	0.1%	4.7%	4.7%	0.1%
	Suburban <sub>LD</sub>		11.9%			19.3%	
Suburban	Suburban <sub>MD</sub>	26.8%	12.6%	0.2%	35.7%	13.8%	0.3%
	Suburban <sub>HD</sub>		1.9%			1.3%	
Water	Water	0.1%	0.5%		0.3%	1.1%	
	Green		49.3%			31.1%	
Grassland/ Agriculture	Green <sub>URB</sub>	56.2%	4.4%		38.8%	2.3%	
	Green <sub>NAT</sub>		3.2%			10.7%	
Woodland	Woodland	4.1%	3.4%		20.5%	15.8%	

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743 Table 5: Linear regression model results for FEH and revised (rc) catchment descriptors. Values were normalized using the  
744 natural logarithm (ln) to normalize data.

	Coefficient ( $\theta_p$ )	Standard error	t-value	p-value
<b>lnURBEXT<sub>rc</sub></b> ( $r^2 = 0.9968$ , $rse = 0.02661$ , $df = 16$ )				
<b>Intercept</b>	-0.03637	0.01526	-2.384	0.0299
<b>lnURBEXT</b>	0.96616	0.04339	22.266	1.82E-13
<b>lnAREA<sub>rc</sub></b> ( $r^2 = 0.9965$ , $rse = 1.426$ , $df = 12$ )				
<b>Intercept</b>	-0.41	0.59442	-0.691	0.503
<b>lnAREA</b>	1.02826	0.01681	61.182	2.41E-16
<b>lnFARL<sub>rc</sub></b> ( $r^2 = 0.8943$ , $rse = 0.1872$ , $df = 16$ )				
<b>Intercept</b>	-0.9723	0.1592	-6.108	1.514E-05
<b>lnFARL</b>	1.9626	0.1631	12.035	1.97E-09

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746 Table 6: Refined list of potential QMED catchment descriptors and metrics. QMED and each descriptor across all sites are  
747 transformed using natural logarithm. Correlations greater than 0.8 are highlighted in bold. Correlations between 0.6 and 0.8 are  
748 shown in italics and underlined.

	QMED	AREA	BFIHOST	SAAR	FARL	URBEXT	PX	PXN	CONTAG	LP <sub>urb</sub>	CONTIG <sub>urb</sub>	CLUMPY <sub>urb</sub>	COHESION <sub>urb</sub>	LP <sub>sub</sub>	CONTIG <sub>sub</sub>	CLUMPY <sub>sub</sub>	COHESION <sub>sub</sub>	COHESION <sub>net</sub>
<b>QMED</b>	1	<b>0.95</b>	-0.38	0.08	-0.38	-0.36	<b>0.82</b>	-0.52	-0.46	0.14	0.28	0.46	<u>0.61</u>	-0.51	-0.5	0.47	0.18	0.42
<b>AREA</b>	<b>0.95</b>	1	-0.41	-0.05	-0.5	-0.53	0.59	<u>-0.7</u>	-0.38	-0.13	-0.35	0.02	0.48	<u>-0.7</u>	-0.56	0.48	0	0.27
<b>BFIHOST</b>	-0.38	-0.41	1	0.48	0.04	-0.08	-0.31	0.11	<u>0.6</u>	-0.27	-0.44	-0.51	-0.54	-0.11	0.04	-0.18	<u>-0.6</u>	-0.47
<b>SAAR</b>	0.08	-0.05	0.48	1	0.19	-0.12	0.12	-0.02	0.36	0.08	-0.28	-0.22	-0.21	-0.32	0.02	-0.06	<u>-0.6</u>	-0.34
<b>FARL</b>	-0.38	-0.5	0.04	0.19	1	<b>0.82</b>	0	<b>0.88</b>	0.3	0.3	0.08	0.05	-0.07	0.53	<u>0.6</u>	-0.42	0.38	-0.3
<b>URBEXT</b>	-0.36	-0.53	-0.08	-0.12	<b>0.82</b>	1	-0.04	<b>0.83</b>	0.5	<u>0.75</u>	0.22	0.51	0.27	0.59	0.43	-0.41	0.22	<u>-0.6</u>
<b>PX</b>	<b>0.82</b>	0.59	-0.31	0.12	0	-0.04	1	-0.18	-0.17	0.29	-0.33	0.29	<u>0.77</u>	-0.57	-0.43	0.34	-0.14	-0.1
<b>PXN<sub>URBEXT</sub></b>	-0.52	<u>-0.7</u>	0.11	-0.02	<b>0.88</b>	<b>0.83</b>	-0.18	1	0.53	0.33	0.49	0.42	-0.12	<u>0.73</u>	<b>0.8</b>	-0.59	0.14	-0.41

<b>CONTAG</b>	-0.46	-0.38	<u>0.6</u>	0.36	0.3	0.5	-0.17	0.53	<b>1</b>	0.35	0.25	0.31	0.01	0.48	0.52	-0.06	0.3	-0.04
<b>LPI<sub>URB</sub></b>	0.14	-0.13	-0.27	0.08	0.3	<u>0.75</u>	0.29	0.33	0.35	<b>1</b>	-0.3	0.4	<u>0.65</u>	0.04	-0.18	0.08	0.08	<u>-0.6</u>
<b>CONTIG<sub>URB</sub></b>	0.28	-0.35	-0.44	-0.28	0.08	0.22	-0.33	0.49	0.25	-0.3	<b>1</b>	0.5	-0.29	<u>0.75</u>	<u>0.68</u>	-0.22	0.48	0.49
<b>CLUMPY<sub>URB</sub></b>	0.46	0.02	-0.51	-0.22	0.05	0.51	0.29	0.42	0.31	0.4	0.5	<b>1</b>	<u>0.61</u>	0.43	0.2	0.16	<u>0.64</u>	0.16
<b>COHESION<sub>URB</sub></b>	<u>0.61</u>	0.48	-0.54	-0.21	-0.07	0.27	<u>0.77</u>	-0.12	0.01	<u>0.65</u>	-0.29	<u>0.61</u>	<b>1</b>	-0.28	-0.5	0.49	0.31	-0.11
<b>LPI<sub>SUB</sub></b>	-0.51	<u>-0.7</u>	-0.11	-0.32	0.53	0.59	-0.57	<u>0.73</u>	0.48	0.04	<u>0.75</u>	0.43	-0.28	<b>1</b>	<u>0.76</u>	-0.36	<u>0.6</u>	0.08
<b>CONTIG<sub>SUB</sub></b>	-0.5	-0.56	0.04	0.02	<u>0.6</u>	0.43	-0.43	<b>0.8</b>	0.52	-0.18	<u>0.68</u>	0.2	-0.5	<u>0.76</u>	<b>1</b>	<u>-0.6</u>	0.15	-0.02
<b>CLUMPY<sub>SUB</sub></b>	0.47	0.48	-0.18	-0.06	-0.42	-0.41	0.34	-0.59	-0.06	0.08	-0.22	0.16	0.49	-0.36	<u>-0.6</u>	<b>1</b>	0.37	0.53
<b>COHESION<sub>SUB</sub></b>	0.18	0	<u>-0.6</u>	<u>-0.6</u>	0.38	0.22	-0.14	0.14	0.3	0.08	0.48	<u>0.64</u>	0.31	<u>0.6</u>	0.15	0.37	<b>1</b>	0.47
<b>COHESION<sub>NAT</sub></b>	0.42	0.27	-0.47	-0.34	-0.3	<u>-0.6</u>	-0.1	-0.41	-0.04	<u>-0.6</u>	0.49	0.16	-0.11	0.08	-0.02	0.53	0.47	<b>1</b>

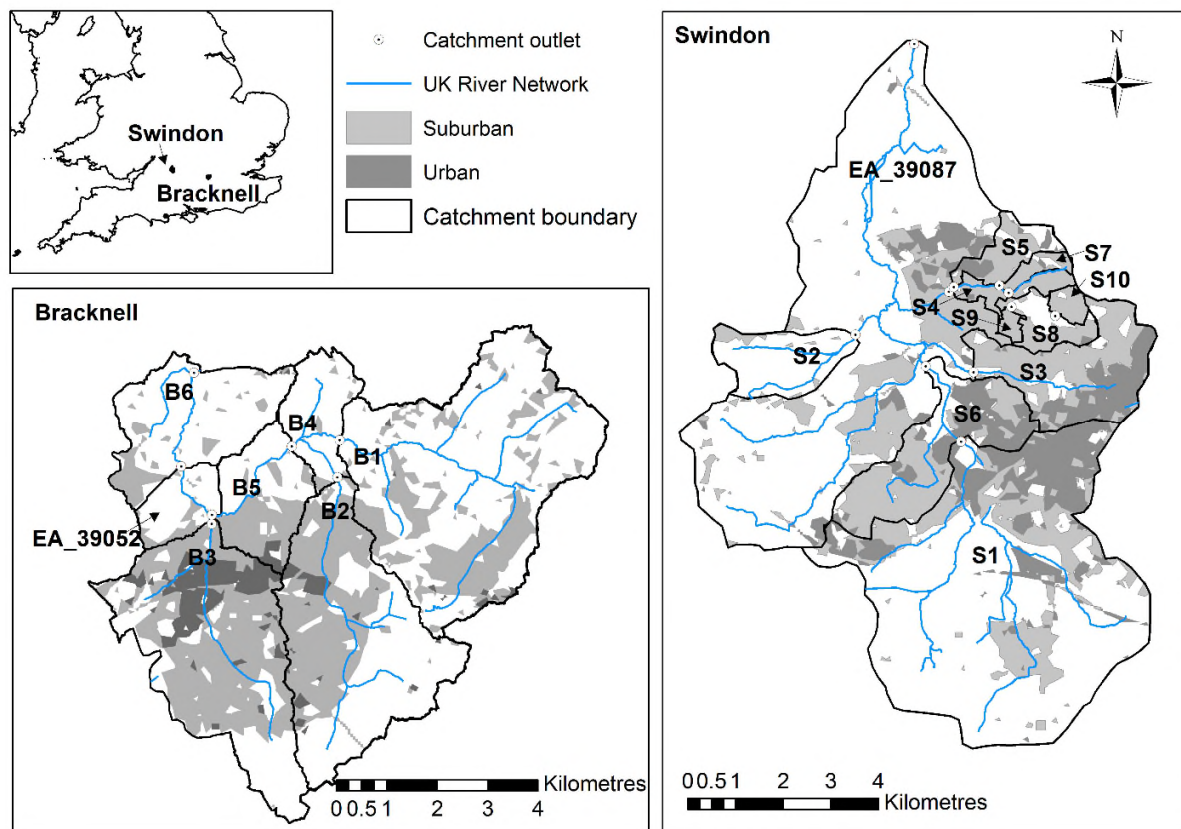
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752 Table 7:  $QMED_{rev}$  and  $QMED_{FEH}$  estimates with linear model performance and differences to observed  $QMED$  (light grey denotes a difference exceeding 10%, medium grey 25%, and dark grey exceeding 50%)

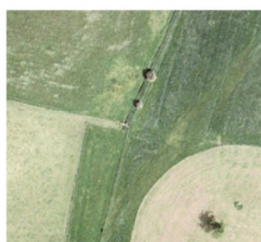
Site_ID	AREA <sub>c</sub> (km <sup>2</sup> )	PX	CONTAG	COHESION <sub>SUB</sub>	QMED <sub>obs</sub> (m <sup>3</sup> /s)	QMED <sub>rev</sub> (m <sup>3</sup> /s) (r <sup>2</sup> =0.984)	Diff ((QMED <sub>rev</sub> - QMED <sub>obs</sub> )/ QMED <sub>obs</sub> )	QMED <sub>FEH</sub> (m <sup>3</sup> /s) (r <sup>2</sup> =0.907)	Diff ((QMED <sub>FEH</sub> - QMED <sub>obs</sub> )/ QMED <sub>obs</sub> )	FARL <sub>c</sub>	URBEXT
S1	28.97	3.88	57.5	95.1	8.84	8.04	-9.1%	6.28	-28.9%	0.97	0.23
S2	3.24	0.2	76.4	81.4	0.64	0.63	-1.6%	0.24	-62.0%	0.85	0.03
S3	5.98	1.68	61.7	98.4	1.38	1.55	12.9%	2.01	46.1%	1	0.57
S4	3.09	1.38	68.0	99.6	1.17	1.10	-5.3%	0.91	-21.9%	1	0.33
S5	2.18	3.53	52.5	96.0	2.94	3.32	12.7%	0.69	-76.6%	1	0.39
S6	35.2	4.28	55.5	96.0	9.37	10.83	15.6%	7.56	-19.4%	0.96	0.29
S7	0.54	1.54	52.7	94.7	0.97	0.82	-15.6%	0.16	-83.9%	1	0.4
S8	2.16	1.07	52.7	98.9	0.80	0.87	9.6%	0.78	-2.3%	1	0.31
S9	0.27	0.66	62.3	100.0	0.25	0.26	4.2%	0.13	-47.5%	1	0.51
S10	0.49	2	93.8	95.1	0.64	0.61	-4.2%	0.15	-77.1%	1	0.37
EA_39087	82.5	3.95	55.5	97.4	13.41	11.35	-15.3%	13.72	2.3%	0.95	0.23
B1	18.37	1.15	51.0	93.6	2.31	2.26	-1.9%	3.19	38.2%	0.88	0.09
B2	12.49	1.69	58.1	98.9	2.97	2.28	-23.1%	1.84	-38.1%	0.94	0.19
B3	12.55	2.76	52.8	99.2	3.90	4.50	15.3%	2.11	-45.9%	0.92	0.37
B4	33.66	2.07	50.0	96.7	5.35	4.02	-24.8%	5.11	-4.4%	0.9	0.12
B5	37.5	1.85	50.4	97.2	5.61	4.14	-26.2%	5.12	-8.6%	0.87	0.13
B6	58.24	2.84	48.3	98.2	10.63	7.88	-25.9%	7.35	-30.8%	0.87	0.17
EA_39052	51.96	3.55	47.9	98.4	9.70	11.67	20.3%	6.35	-34.6%	0.86	0.19
Mean	21.6	2.2	58.2	96.4	4.5	4.2	-3.5%	3.5	-27.5%	0.9	0.3

754 **6 Figures**



755  
 756 *Figure 1: Study locations identifying Environment Agency (EA) gauging stations and selected sub-catchments for Bracknell (B)*  
 757 *and Swindon (S), and showing Urban and Suburban extent: labels demote study catchments names (note some catchments are*  
 758 *nested)*

Urban

Suburban<sub>LD</sub>Suburban<sub>MD</sub>Suburban<sub>HD</sub>Green<sub>URB</sub>

Green

Green<sub>NAT</sub>

Water

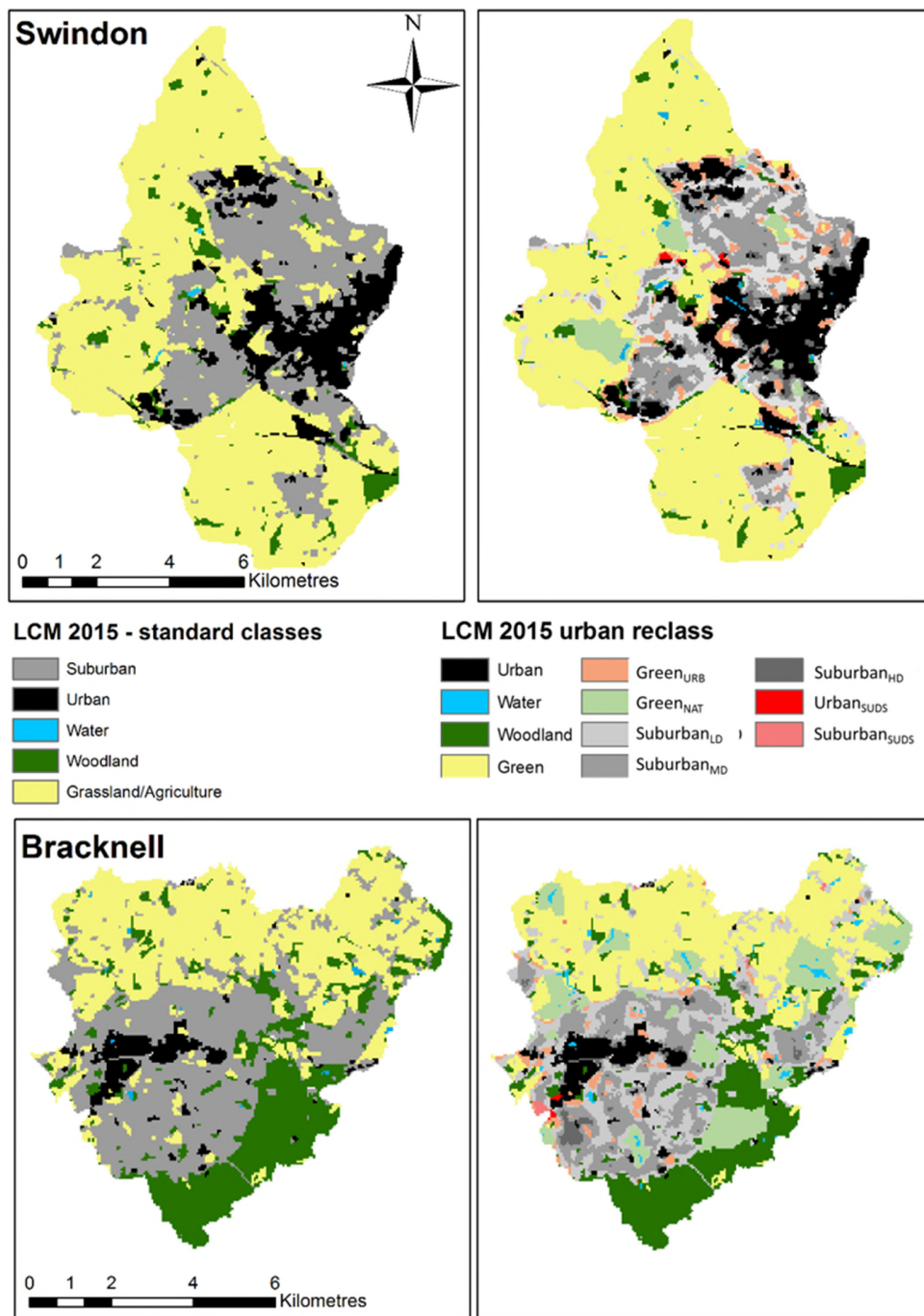
759

760

761

Figure 2: Refined urban land cover classes (scale 1:800): LD = Low Density, MD = Medium density, HD = High Density, URB = Urban, NAT = Natural.





762  
 763 *Figure 3: Comparison of land cover classes using standard and refined urban reclassification for both Swindon and Bracknell*  
 764 *town (2015)*

765

766 **Appendix**

767 Table 1: Class names and numbers for the vector data– the vector data set is the master data set  
 768 from which the other products are derived. Note the table contains class numbers for some  
 769 classes not found in the Thames Basin area – this is to allow the classifications to be extended to  
 770 wider areas if required in the future.

Class number	Class name	Reclass number	Reclass name
1	Broadleaved / mixed woodland	4	Natural
2	Coniferous woodland	4	Natural
3	Arable	5	Agricultural/managed
4	Improved grassland	5	Agricultural/managed
5	<del>Neutral grassland</del>	na	
6	Calcareous grassland	4	Natural
7	<del>Acid grassland</del>	na	
8	<del>Fen, marsh, swamp</del>	na	
9	Dense dwarf shrub heath (heather)	4	Natural

10	Open dwarf shrub heath (heather grassland)	4	Natural
<del>11</del>	<del>Bog (deep peat)</del>		
12	Inland rock	4	Natural
<del>13</del>	<del>Sea / Estuary</del>		
14	Water (inland)	3	Water
<del>15</del>	<del>Coastal</del>		
<del>16</del>	<del>Saltmarsh</del>		
17	Suburban	1	Suburban
18	Urban	2	Urban

771

772 Table 2: ArcGIS method for deriving refined Suburban classes (LCM\_RC1) based on density

773 information from OSMM. Input data LCM2015 (Suburban), OSMM (buildings).

Step	Tool and data	Description
1	Select 'buildings' from OSMM attribute table and make new polygon layer	

2	<b>Polygon to raster</b> (Step1) (5m)	
3	<b>Reclassify</b> (no data 0, building 1)	
4	<b>Aggregate</b> to 50m (mean)	
5	Identify suitable breaks – test 10 selected areas of different development type and density using 3 classes.	0.13, 0.19 identified as breaks.
6	<b>Reclassify</b> using breaks (Step 5)	Set grids as 11, 12, 13
7	<b>Clip</b> LCM 2015 to catchment	1 = Suburban
8	<b>Clip</b> (5) to catchment	
9	<b>Raster Calculator:</b> Con(Step7==1,Step8,Step7)	Re-classes Suburban grids as 11 (LD), 12 (MD), or 13 (HD)
10	<b>Data export</b>	LCM_RC1

774

775 Table 3: ArcGIS method for deriving refined Water classes (LCM\_RC2) based on water features

776 indicated on OSMM. Input data: LCM\_RC1 (3), OSMM (water).

<b>Step</b>	<b>Tool and data</b>	<b>Description</b>
-------------	----------------------	--------------------

1	Select 'water' from OSMM attribute table and save as new layer	
2	<b>Polygon to raster</b> (Step1) (1m)	
3	<b>Reclassify</b> (no data 0, water 3)	
4	<b>Aggregate</b> to 50m (mean)	
5	Identify suitable breaks – test 10 selected areas of water feature (river-lake) using 2 classes.	0.23 identified as suitable break – not encompassing very small features or rivers.
6	<b>Reclassify</b>	0 no water, 3 water.
7	<b>Clip</b> (Step 6) to catchment	
8	<b>Raster Calculator:</b> Con(((Step6==3) & (LCM_RC1 != 3),3,LCM_RC1)	Converts non LCM_RC1 water grids to 3.
9	<b>Data export</b>	LCM_RC2

777

778 Table 4: ArcGIS method for deriving refined greenspace classes (LCM\_RC3) based on spatial  
779 statistics of LCM\_RC2 greenspace (5). Input data: LCM\_RC1 (5). Method rationale is to  
780 identify small greenspaces in urban areas and separate from larger greenspaces in urban areas or  
781 outside urban areas. Key method refinement was altering step 2 Focal Statistics size until smaller  
782 greenspaces in urban areas could be separated from larger less-urban greenspaces at the fringes

783 or in areas of ingress. This took some 10 iterations – from 100m to 1km. 250m was an ideal  
 784 patch size below which urban greenspaces such as parks and playing fields could be separated  
 785 from less managed surfaces such as parks and fields.

<b>Step</b>	<b>Tool and data</b>	<b>Description</b>
1	<b>Reclassify</b> LCM_RC2	Urban and Suburban HD = 3, Suburban M D & LD = 2, Greenspace and Natural =1, Water = 0.
2	<b>Focal Statistics:</b> circle, mean, 5.	Mean value (0-3) in 250m circle around each grid
3	<b>Reclassify</b> (5 classes – values 0-3)	1 (1), 2 (1.5), 3 (2), 4 (2.5), 5 (3)
4	<b>Clip</b> (step 3 to catchment)	
8	<b>Raster Calculator:</b> Con((LCM_RC2==5) & (Step4>2),6, LCM_RC2)	Converts selected LCM_RC2 Greenspace to Green <sub>URB</sub> (6)
9	<b>Data export</b>	LCM_RC3

786

787 Table 5: ArcGIS method for deriving ‘Green<sub>NAT</sub>’ class (RC4) based on Natural England mapping  
 788 of Local Nature Reserves, Country Parks, and Woodland and Pasture. Input data: LCM\_RC3,  
 789 Local Nature Reserves, Country Parks, and Woodland and Pasture.

<b>Step</b>	<b>Tool and data</b>	<b>Description</b>
1	<b>Merge</b> Natural England datasets	
2	<b>Clip</b> merged dataset (Step2) to catchment	
3	<b>Add Field:</b> Nature (7)	
4	<b>Polygon to Raster</b> (5m), Step3 (7)	
8	<b>Aggregate</b> (50m ) Mean	
9	<b>Reclassify: No data 0, Nature 7</b>	Set extent to catchment + Snap
10	<b>Raster Calculator:</b> Con((LCM_RC3=!3) & (Step9==7),7,LCM_RC3)	Convert non-water features to Greenspace natural - Green <sub>NAT</sub>
	<b>Data export</b>	LCM_RC4

790

791 Table 6: Geoprocessing to determine areas of Urban<sub>SUDS</sub> or Suburban<sub>SUDS</sub>– post 2010

792 developments only

<b>Step</b>	<b>Tool and data</b>	<b>Description</b>
1	<b>Stage 1: Process SuDS maps</b>	Using the British Geological Survey (BGS) – SuDS

	<p>The following features were selected from each layer as being indicative of features that would negate the possibility of SuDS installation:</p> <p>Drainage summary – identified areas with ‘Very significant constraints are indicated’</p> <p>Ground stability summary – identified areas with ‘Significant potential for geohazard’ and ‘Very significant constraints are indicated’</p> <p>Groundwater protection summary – identified areas with ‘Considerable susceptibility’ and ‘Very significant constraints are indicated’</p>	<p>infiltration map (SIM: Dearden, 2016) - that accounts for such factors has been used to locate sites, indicating SuDS suitability</p>
2	Merge the SuDS layers in step 1 to one polygon dataset.	Single layer showing areas of SuDS not being suitable.
3	Clip SuDS layer to catchment – and add field SuDS with value 55.	
4	Polygon to Raster, 50m, snap LCM2015	Convert to raster (50m)
	Reclassify RC5 as SuDS raster with 1=Suds potential, 44=no potential, and clip to catchment > RC5	Reclassify and clip to final SuDS raster RC5



8	<p><b>Stage 2: Identify areas of new (post 2010) development</b></p> <p>Raster calculator: <math>\text{Con}((\text{RC4}==2) \&amp; (\text{LCM2010}&gt;2),14,\text{RC4}) &gt; \text{RC4}</math></p> <p>Raster calculator:  <math>\text{Con}((\text{RC4}==11) (\text{RC4}==12) (\text{RC4}==13) \&amp; (\text{LCM2010}&gt;2),15,\text{RC4}) &gt; \text{RC4}</math></p> <p>Data export : SuDS</p>	<p>Identify new areas of development – and reclass as either Urban post 2010 (14) or Suburban post 2010 (15) (SuDS)</p>
9	<p><b>Stage 3: Identify areas likely to have SuDS</b></p> <p>Convert Urban post-2010 to Urbans<sub>SUDS</sub> (141):  <math>\text{Con}((\text{RC5}==14)\&amp;(\text{SuDS}&lt;44),141,\text{RC5})</math></p> <p>Convert Suburban post-2010 to Suburbans<sub>SUDS</sub> (151):  <math>\text{Con}((\text{RC5}==15)\&amp;(\text{SuDS}&lt;44),151,\text{RC5})</math></p> <p>Convert back areas that were not suitable to their previous classes – removes class 14,15:  <math>\text{Con}((\text{RC5}==14) (\text{RC5}==15),\text{RC4},\text{RC5})</math></p> <p>Export data&gt;RC6</p>	<p>Identify areas that are post 2010 and have SuDS potential.</p>

795 Table 7: Method for reclassifying catchment area –  $AREA_{rc}$  - manipulated using the ArcGIS 10.3

796 Hydrology toolset in combination with manual delineation of artificial drainage areas

Step	Tool and data	Description
1	<b>Hydrology</b> tools were used to delineate natural drainage areas to manually mark pour points that identify monitoring locations.	
2	For locations where there was no natural drainage, the contributing drainage area was manually delineated using a combination of drainage map and topographical mapping from OSMM	
3	For catchments where there was a visual discrepancy between the natural drainage area and artificial drainage (B3, S1, S3 - S10), the natural drainage polygon was manually altered to encompass areas where artificial drainage crosses natural boundaries derived from the DEM.	

797

798 Table 8: Initial list of landscape metrics and associated values: including 5 hydrological metrics, 3 landscape metrics, 10 Urban class  
 799 metrics, 10 Suburban class metrics, and 2 Green<sub>NAT</sub> class metrics. Blank values for certain sites indicate catchments with none of this  
 800 class present.

Site_ID	Hydro_Metrics					Landscape metrics			Urban class metrics										Suburban class metrics							Green <sub>NAT</sub> class metrics				
	INDO	PK	PK <sub>u</sub>	PK <sub>u</sub> NET	PK <sub>u</sub> NET <sub>u</sub>	LSI	CONTAG	MESH	PLAND <sub>urb</sub>	LP <sub>urb</sub>	TE <sub>urb</sub>	ED <sub>urb</sub>	PARA_MN <sub>urb</sub>	PARA_AM <sub>urb</sub>	CONTIG_MN <sub>urb</sub>	CONTIG_AM <sub>urb</sub>	CLUMP <sub>urb</sub>	COHESION <sub>urb</sub>	PLAND <sub>sub</sub>	LP <sub>sub</sub>	TE <sub>sub</sub>	ED <sub>sub</sub>	PARA_MN <sub>sub</sub>	PARA_AM <sub>sub</sub>	CONTIG_MN <sub>sub</sub>	CONTIG_AM <sub>sub</sub>	CLUMP <sub>sub</sub>	COHESION <sub>sub</sub>	PLAND <sub>nat</sub>	COHESION <sub>nat</sub>
S1	4.42	3.88	0.59	3.88	0.30	8.09	57.48	889	16.03	10.96	53450	18.59	477	135	0.36	0.81	0.82	96.23	18.03	6.66	78650	27.36	480	171	0.36	0.76	0.76	95.09	0.76	0.47
S2	1.87	0.20	0.12	0.20	0.06	2.97	76.41	238											10.51	6.26	6100	18.86	417	271	0.39	0.61	0.69	81.36	0.00	0.00
S3	3.16	1.68	0.89	1.68	0.72	4.77	61.72	214	32.57	31.27	15800	26.42	484	108	0.34	0.85	0.85	97.68	55.77	50.79	26150	43.73	407	111	0.44	0.84	0.74	98.38	0.00	0.00
S4	1.94	1.38	0.87	1.38	0.85	3.25	68.04	199	1.53	1.05	1150	3.70	305	295	0.55	0.57	0.82	70.68	79.31	79.31	8850	28.50	80	80	0.89	0.89	0.66	99.64	9.66	0.84
S5	0.59	3.53	0.96	3.53	0.81	4.02	52.52	45	15.32	9.91	5900	27.19	440	214	0.40	0.70	0.77	85.53	62.10	38.82	10050	46.31	333	121	0.57	0.83	0.70	96.05	0.46	0.17
S6	6.00	4.28	0.73	4.28	0.59	8.79	55.45	804	18.61	13.56	75100	21.48	446	126	0.40	0.82	0.83	97.06	24.27	10.43	100400	28.72	449	129	0.40	0.82	0.81	95.98	0.62	0.47
S7	0.31	1.54	0.88	1.54	0.85	2.77	52.68	19	5.94	3.65	1250	22.83	400	400	0.44	0.44	0.70	66.01	81.74	48.86	2650	48.40	220	170	0.69	0.76	0.19	94.72	0.00	0.00
S8	1.42	1.07	0.70	1.07	0.70	2.77	52.68	19	1.50	1.50	650	3.00	277	277	0.60	0.60	0.94	74.81	72.55	70.47	7100	32.76	271	92	0.63	0.87	0.72	98.88	13.84	0.84
S9	0.41	0.66	1.00	0.66	1.00	3.10	62.34	112											99.08	99.08	100	3.67	122	122	0.83	0.83	0.00	99.95	0.00	0.00
S10	0.24	2.00	0.97	2.00	0.97	1.62	93.82	27											18.03	6.66	78650	27.36	480	171	0.36	0.76	0.76	95.09	0.00	0.00
EA_39087	10.30	3.95	0.49	1.97	0.25	11.92	55.55	1232	4.56	3.26	43500	7.47	467	168	0.37	0.77	0.81	93.58	34.05	23.95	209000	35.89	467	110	0.37	0.85	0.81	98.20	3.24	0.55
B1	4.59	1.15	0.29	0.57	0.14	8.81	50.96	360	0.71	0.15	5200	2.83	468	431	0.37	0.41	0.54	59.62	26.01	11.89	74900	40.80	456	170	0.39	0.76	0.74	93.65	12.75	0.53
B2	4.94	1.69	0.67	0.84	0.33	5.26	58.08	366	3.42	1.44	9750	7.80	465	248	0.38	0.66	0.74	78.94	43.09	41.75	37050	29.65	476	86	0.37	0.88	0.85	98.89	13.50	0.63
B3	3.83	2.76	0.84	1.38	0.42	6.56	52.81	385	15.35	13.30	25150	20.06	374	139	0.48	0.81	0.83	95.90	53.11	51.63	54000	43.06	494	96	0.36	0.87	0.78	99.24	3.87	0.64
B4	5.66	2.07	0.35	1.04	0.17	9.89	49.96	470	1.66	0.53	15000	4.46	466	291	0.38	0.60	0.68	74.27	30.68	17.11	117400	34.88	450	124	0.39	0.83	0.80	96.74	12.75	0.64
B5	7.60	1.85	0.37	0.92	0.19	10.23	50.35	571	1.91	0.63	17200	4.59	465	263	0.38	0.64	0.71	80.54	31.78	19.15	130750	34.88	456	119	0.38	0.84	0.80	97.19	11.80	0.64
B6	9.24	2.84	0.45	1.42	0.23	12.44	48.34	876	4.56	3.26	43500	7.47	467	168	0.37	0.77	0.81	93.58	34.05	23.95	209000	35.89	467	110	0.37	0.85	0.81	98.20	10.65	0.65
EA_39052	7.70	3.55	0.53	1.78	0.26	11.80	47.89	753	4.56	3.26	43500	7.47	467	168	0.37	0.77	0.81	93.58	34.05	23.95	209000	35.89	467	110	0.37	0.85	0.81	98.20	10.73	0.60

801

802

# Refining flood estimation in urbanized catchments using landscape metrics, Landscape and Urban Planning

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2018-03-22

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Miller JD, Brewer T. (2018) Refining flood estimation in urbanized catchments using landscape metrics. *Landscape and Urban Planning*, Volume 175, July 2018, pp. 34-49

<https://doi.org/10.1016/j.landurbplan.2018.02.003>

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