Improved Hydrological Modelling of Urban Catchments Using Runoff Coefficients

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Abstract

The expansion of built-up areas within urban and peri-urban river catchments has the potential to increase flooding. Hydrological modelling of these catchments is an important tool to analyse and manage the increasing flood hazard, but it requires an understanding of the areas contributing to runoff from the urban parts of the catchment. This is difficult as in many catchments fine resolution data is not available and the connectivity of the impervious areas, sewer networks and the drainage network are not well understood. In this research, we present a novel approach for calculating the separate and combined sewer fractions for an urban river catchment and use these fractions to improve hydrological modelling of the catchment. The fractions are calculated using monthly runoff coefficients from paired rural/urban catchments, with the procedure carried out for 20 highly urbanized catchments within the UK. The calculated fractions have been compared with the OS MasterMap high-resolution land use data set and also verified against results obtained with the standard method of using hourly rainfall-runoff data in an event-based approach. Hydrological modelling using the physically-based Shetran system demonstrates improved results using the approach developed here. For urban and peri-urban catchments without fine resolution sewer and hydrological data, it is recommended that this new method should be applied before detailed hydrological modelling of the catchments is undertaken in order to evaluate the flows to the drainage network and determine the impact of urbanisation on the water balance.

Highlights

- Separate and combined sewer fractions are calculated for urban catchments
- Method requires monthly rainfall-runoff data from paired rural/urban catchments
- Verification against more data intensive methods shows good agreement
- Hydrological modelling using the novel approach shows improved results
- Results demonstrate the impact of urbanisation on the catchment water balance

Keywords

Urban drainage; Effective impervious area; Runoff coefficients; Sewer systems; Paired rural/urban catchment; Hydrological modelling

1. Introduction

Currently around 55% of the world's population is living in urban areas, a proportion that is expected to increase to 68% by 2050 (United Nations, 2019). The impacts of urbanization on water quantity and quality are well documented (e.g. Arnold and Gibbons, 1996; Jacobson, 2011; Miller and Hutchins, 2017, Oudin et al., 2018). Regarding water quantity, a main concern with urban expansion is reduced time to peak (flashiness), enhanced peak flows and increased runoff volumes (e.g. McMahon et al., 2003, Miller et al., 2014). For water quality, the main issue is the increased mobilisation and transport of contaminants into receiving waters (McGrane, 2016; de Mello et al., 2018; Salerno et al., 2018). Understanding and managing the hydrology of highly urbanized catchments is complicated by the role of the sewer network and its linkages to impervious areas and water courses. Separate storm sewer systems contribute runoff directly into watercourses, while combined storm and sewerage water systems feed into water treatment works, which are in many cases located outside the catchment.

Hydrological modelling in an urban environment is an important tool in understanding the increasing flood risk and to manage flood hazards, for example, understanding the benefits of the use of green infrastructure in urban areas (Ellis, 2013; Epps and Hathaway, 2018, O'Donnell et al., 2020).

However, the modelling is challenging due to the highly heterogeneous nature of urban catchments and specific hydrological processes such as the sewer network. Effective modelling requires not only a measure of the impervious areas but also an understanding of the connectivity of impervious areas, the sewer systems and the drainage network. For an individual building, road or car park it is possible to measure the proportion of the precipitation that lands on impervious areas which enters the sewer network (Lee and Heaney, 2003). However, the patchwork of green and built-up areas complicates analyses when considering the larger scale (Alberti et al., 2007; Seo et al., 2013).

Impervious areas such as roads, buildings and car parks contribute flow to the sewer system but may also drain into adjacent pervious green areas. Gardens are predominantly pervious and allow infiltration, but may have impervious and drained sections (Warhurst et al., 2014; Kelly, 2018). Two widely used terms in urban hydrology that consider these issues of impervious area and hydraulic

connectivity are the Total Impervious Area (TIA) and the Effective Impervious Area (EIA). These terms are defined below and are used in the verification of the approach developed in this work.

The Total Impervious Area (TIA) is the impervious area as a fraction of the total catchment area (O'Driscoll et al., 2010; McGrane, 2016). There is no standard methodology to calculate TIA, with a number of techniques utilized including ground mapping and the classification of satellite data. Consequently, the comparison of results between studies is difficult (e.g. Slonecker and Tilley, 2004). Another shortcoming of TIA for water quantity and quality management issues is that it does not distinguish between impervious areas that are hydraulically connected to the sewer system/drainage network, and those which drain into pervious areas (Lee and Heaney, 2003; Shuster et al., 2005; Roy and Shuster, 2009; Burns et al., 2015; Ebrahimian et al., 2016b).

The Effective Impervious Area (EIA) is defined as the impervious area that is hydraulically connected to the sewer system/drainage network as a fraction of the total catchment area, so it is an important value in determining the actual runoff (Boyd, et al., 1993; Jones et al., 2003; Ebrahimian et al., 2016a). The EIA is usually calculated from an analysis of the event-based rainfall-runoff response (Ebrahimian et al., 2016a), although alternative methods are used (Jones et al., 2003; Han and Burian, 2009; Epps and Hathaway, 2018). Jacobsen (2011), Miller et al. (2014) and Ebrahimian et al. (2016a) have compared EIA and TIA values and found significant variation depending on local factors including the storm drainage network and flood attenuation features. McGrane (2016), Janke et al. (2011) and Fletcher et al. (2013) have all highlighted that quantifying the EIA is a research goal in urban hydrology.

This work focuses on the hydrological modelling of catchments that contain urban, peri-urban and rural areas (Fletcher et al. 2013, Salvadore et al. 2015; Hutchins et al., 2017). In distributed or semi-distributed hydrological models of urban and peri-urban areas the catchments are generally split into a pervious fraction, that takes into account the higher infiltration and delayed runoff in the 'green areas' within the catchment, and an impervious fraction, which accounts for the reduced infiltration and faster runoff in the 'built-up' areas. Examples include the SWAT model (Sisay et al. 2017), the DHSVM model (Cuo et al. 2008) and the VIC model (Yang et al. 2011). Coupled hydrological/hydraulic models, that may be applied to small catchment areas, incorporate detailed knowledge of the storm drainage network. Examples include SWMM (Palla and Gnecco, 2015), MIKE URBAN (Bisht et al., 2016) and CityCAT (Glenis et al., 2018). However, in many cases there is no information on the storm drainage network, in which case simpler models are used (Coutu et al. 2012; Petrucci and Bonhomme, 2014). In order to understand the flow pathways, as well as incorporating impervious area, it is important to establish the fraction of water that flows into

combined sewers, which is removed from and treated outside the catchment, and separate sewers, where the water flows directly into the channel drainage network and to the catchment outlet (Vrebos et al. 2014).

In this work the following key fractions of a catchment from a hydrological modelling viewpoint are defined:

- a) The separate sewer fraction (F_s). Runoff generated in fraction F_s reaches the catchment outlet via impervious areas and the sewer system/drainage network. This corresponds to the EIA.
- b) The combined sewer fraction (F_c). Runoff generated in fraction F_c flows into the combined sewer system which is removed and treated outside the catchment.
- c) The pervious fraction (F_p). Runoff generated in fraction F_p reaches the catchments outlet by typical 'green area' pathways including subsurface flow and channel-aquifer interactions.

The three key objectives in this work are:

- Develop a novel approach which uses monthly rainfall-runoff records from paired rural/urban catchments to provide estimates of the three fractions (F_s , F_c , and F_p). The approach is applied to 20 urbanized catchments in the UK.
- Verify the three fractions (F_s , F_c , and F_p). For each of the 20 catchments compare the values ($F_s + F_c$) with TIA values calculated using standard land-use classifications, two of which use fine resolution ground mapping and one using satellite data. Also for nine catchments, compare F_s against those calculated using the more data intensive event-based rainfall-runoff response method.
- Conduct a hydrological modelling study for three of the 20 catchments using the F_s , F_c and F_p fractions calculated here and additionally using standard approaches. This study is intended to demonstrate the importance of using the correct separate and combined fractions within hydrological models.

These three objectives can be seen on the overall flow chart of the work (Fig. 1).

Fig. 1. Flow chart showing the overall methodology of the research

2. Data and methods

2.1 Catchment selection

The choice of UK catchments for inclusion in this study was firstly determined by the availability of 25 years of concurrent monthly precipitation and flow records. Although there is no strict distinction between rural and urban catchments, research (e.g. Booth and Jackson, 1997) suggests a 10% impervious area can have a significant impact on the water mass balance. Here, rural catchments were specified as having an impervious cover of less than 8%, and with no concentrated settlements, and urban catchments greater than 14%. (The OS MasterMap data set was used to define these percentages, see Section 2.3).

Catchments were excluded where significant transfers of surface water or groundwater abstractions were reported by the UK National River Flow Archive (NRFA). To reduce heterogeneity when selecting rural/urban catchment pairs, the catchment outfalls were required to be within 80km, the difference in mean annual precipitation less than 15% and the Base Flow Index (BFI) values (Gustard et al. 1992) within 0.15. Using these selection criteria, 20 urban and 5 rural catchments were identified, which were clustered around 5 separate urban conurbations and ranged in area from 9.9km² to 405.6 km² (Fig. 2 and Table 1).

To provide a demonstration of the approach, the Ouseburn catchment (Newcastle upon Tyne) is considered as a case study (Fig. 3). Situated on the Ouseburn river are the nested “rural” gauge at

Woolsington (11.4 km²) and the downstream “urban” gauge at Crag Hall (53.8 km²). (Note, this is the only pair of nested rural/urban catchments included in the study.) Digital maps of the sewer network within the Ouseburn catchment are available (Newcastle City Council, 2015), which are used to verify the estimates of the separate and combined sewer fractions (Section 4.3). The Ouseburn is also included as part of the hydrological modelling study that shows the importance of using the correct combined and separate sewer fractions.

Fig. 2. Location of the selected 20 urban and five rural catchments within the UK

Table 1. The selected five rural and 20 urban UK catchments, separated out in relation to the nearest urban conurbation. Rural catchments in bold. For LCM 2007 and OSMM see Section 2.3 and for Effluent inputs see Section 3.1

Nearest city	Catchment number	Catchment name	Area (km ²)	Annual precipitation (mm)	Effluent inputs (mm/year)	Total Impervious Area (TIA)			Separate sewer fraction, F _s	Combined sewer fraction, F _c	Pervious fraction, F _p	Separate sewer fraction, F _s – event based approach
						LCM 2007	OSMM	OSMM+ (inc. gardens)				
Birmingham	54096	Hadley Brook at Wards Bridge	54.0	699	0	0.02	0.04	0.08				
	28003	Tame at Water Orton	405.6	766	110	0.48	0.37	0.64	0.27	0.32	0.41	0.24
	28039	Rea at Calthorpe Park	73.9	808	49	0.41	0.32	0.63	0.18	0.27	0.55	0.20
	28066	Cole at Coleshill	119.6	737	24	0.36	0.30	0.59	0.16	0.27	0.57	0.17
	54063	Stour at Prestwood Hospital	89.2	747	73	0.35	0.28	0.52	0.24	0.25	0.51	
Leeds	27064	Went at Walden Stubbs	86.3	618	15	0.05	0.07	0.09				
	27081	Oulton Beck at Farrer Lane	25.1	662	0	0.22	0.21	0.36	0.11	0.24	0.65	0.11
London	37011	Chelmer at Churchend	72.8	627	0	0.01	0.03	0.06				
	37018	Ingrebourne at Gaynes Park	44.8	608	36	0.16	0.14	0.27	0.12	0.0	0.88	
	37019	Beam at Bretons Farm	51.5	602	36	0.31	0.24	0.48	0.13	0.19	0.68	
	37031	Crouch at Wickford	70.2	589	6	0.24	0.20	0.36	0.11	0.21	0.68	0.12
	37033	Eastwood Brook at Eastwood	9.9	573	10	0.39	0.31	0.67	0.22	0.37	0.41	0.18

Manchester /Liverpool	38007	Canons Brook at Elizabeth Way	20.7	621	0	0.27	0.26	0.44	0.29	0.01	0.70	
	38014	Salmon Brook at Edmonton	22.8	668	0	0.22	0.18	0.38	0.14	0.01	0.85	
	38022	Pymmes Brook at Edmonton Silver Street	40.5	675	0	0.45	0.35	0.68	0.41	0.01	0.58	
	39049	Silk Stream at Colindeep Lane	30.8	689	0	0.35	0.30	0.57	0.26	0.16	0.58	
	39092	Dollis Brook at Hendon Lane Bridge	23.7	692	0	0.26	0.22	0.46	0.18	0.10	0.72	
	39131	Brent at Costons Lane Greenford	146.2	679	0	0.44	0.37	0.66	0.28	0.18	0.54	
	39137	Yeading West at Gutteridge Wood	17.9	669	0	0.41	0.35	0.70	0.29	0.33	0.38	
	68020	Gowry at Bridge Trafford	148.7	730	0	0.02	0.04	0.08				
	69013	Sinderland Brook at Partington	44.7	801	66	0.35	0.30	0.53	0.10	0.19	0.71	
	69030	Sankey Brook at Causey Bridges	147.7	922	74	0.19	0.19	0.30	0.18	0.0	0.82	0.18
Newcastle	69032	Alt at Kirkby	96.6	885	73	0.33	0.29	0.45	0.18	0.08	0.74	0.21
	23018	Ouseburn at Woolsington	11.4	695	0	0.07	0.07	0.12				
	23016	Ouseburn at Crag Hall	53.8	697	0	0.30	0.25	0.41	0.11	0.19	0.70	0.12

2.2 Precipitation and discharge data

Daily precipitation data were available for a 25-year period (1990 to 2014, inclusive) from a national 1km gridded rainfall product (Lewis et al., 2018b). Catchment boundary data from the NRFA were extracted for the calculation of catchment areal averaged precipitation totals (National River Flow Archive, 2017). Daily discharge data (1990 to 2014) and associated catchment descriptors were also extracted from the NRFA. Using the catchment area, the discharge at the outlet was converted to monthly runoff (mm) and divided by the areal averaged monthly precipitation to calculate the monthly runoff coefficients.

In addition to the daily precipitation and discharge data, 25 years of hourly rainfall-runoff records were obtained for nine of the urban catchments. These data were used in the verification of the derived separate sewer fraction (Section 4.2).

Fig. 3. The Ouseburn at Woolsington (23018) and the Ouseburn at Crag Hall (23016) case study catchments. The urban areas are highlighted either as blue (separate sewers) or red (combined sewers)

2.3 Total impervious fraction

In this work three alternate estimates of the TIA were derived from spatially distributed data sources (Table 2). These estimates were used in the assessment of the impervious fraction ($F_s + F_c$) calculated in this work using the monthly runoff coefficients. Two of the three estimates were derived from the OS MasterMap Topography Layer and the other estimate uses the UK Land Cover Map 2007 (LCM 2007) remotely sensed data set (Morton et al. 2014). The OS MasterMap Layer is a vector dataset of the ground mapping of individual features that are hierarchically assigned to descriptive groups including roads, buildings, and gardens and then to make classes. The make classes include “manmade”, constructed features such as areas of concrete and paved-areas, “natural”, non-manmade features such as vegetation, and “multiple”, a mixture of natural and manmade surfaces. Here, the features were classified as either pervious or impervious (Table A.1). However, the assignment of the feature type “General Surface; Multiple”, is complicated as it includes gardens, which may have been paved for car parking, contributing runoff to adjacent roads and other impervious areas drained by sewers. It is expected that paved gardens and highly compacted urban soils will behave as an impervious part of the catchment (Warhurst et al, 2014), while well-established gardens will allow infiltration and so be a pervious part of the catchment. To provide a lower and an upper estimate of TIA, all gardens were firstly assigned as pervious (hereinafter termed OSMM) and then impervious (OSMM+).

Table 2. Total Impervious Area (TIA) data sources

Name	Resolution	Data Source	Gardens
LCM 2007	25m	Satellite	Insufficient resolution to categorize
OSMM	Vector data converted to 1m raster	Ground mapping	Included in pervious fraction
OSMM+	Vector data converted to 1m raster	Ground mapping	Included in impervious fraction

LCM 2007 is derived from the classification of satellite images and digital cartography and is widely used in hydrological and ecological studies (e.g. Miller and Hess, 2017). It has a 25m grid resolution, hence the detailed patchwork of built-up and green areas found in urban catchments is poorly represented. There are 23 different classes, including an urban and a suburban assignment. Miller

and Grebby (2014) suggest calculating TIA as equal to the urban fraction plus half the suburban fraction. This fraction provides the third estimate of TIA used in this work.

The TIA values derived from the LCM 2007, OSMM and OSMM+ data for the 25 catchments are provided in Table 1. For the urban catchments, the TIA values derived from the LCM 2007 data set fall between the two values derived from the OS MasterMap layer but are closer to those with the assignment of gardens as pervious areas (OSMM). For the rural catchments, the LCM 2007 values are smaller than those derived from both methods using the OS MasterMap layer. This appears to be because small isolated features, such as farm buildings, are not included in the LCM 2007 impervious area due to the coarse pixel size (25m) relative to the size of the features. An example of the assignment of land-use types is provided in Appendix A1 for a suburban area within the Ouseburn case study catchment at Crag Hall.

2.4 Event based rainfall-runoff

In this work a new method is developed using monthly runoff coefficients to give an estimate of the separate sewer, (F_s), combined sewer (F_c) and pervious (F_p) fractions. If hourly or sub-hourly rainfall and discharge data are available then the standard method of calculating the EIA (which corresponds to F_s in this work) in catchments less than 20km² is through the analysis of the event based rainfall-runoff response (Boyd, et al., 1993; Jones et al., 2003; Ebrahimian et al., 2016b; Epps and Hathaway, 2018). The new approach has two advantages over this standard event-based rainfall-runoff approach. Firstly, it uses more readily available data sets. For example, it is much easier to obtain daily or monthly river discharge data than hourly/sub hourly discharge data. In the UK, the National River Flow Archive (2017) has daily discharge records for over 1,500 gauging stations and the GRDC (2019) has daily and monthly discharge data for more than 9,900 stations from 159 countries. Secondly, the fraction F_c , where generated runoff in combined sewers is removed from and treated outside the catchment, cannot be estimated using the event-based rainfall-runoff response, as there is no flow past the catchment outlet. However, the event-based rainfall-runoff response is a useful method to verify the results produced using the new method.

Twenty-five years of hourly rainfall and runoff data were obtained for nine of the urban catchments including the Ouseburn at Crag Hall case study catchment. For these nine catchments, events were extracted subject to there being no precipitation in the 12 hours prior to the event and none in the subsequent 48 hours (this simplifies baseflow separation). Once extracted, the baseflow was removed using the master recession curve method (Posavec et al. 2010). Following the approach of Ebrahimian et al (2016b), each event was classified as either an EIA sourced or combined event. The

discharge in EIA sourced events is assumed to only come from impervious areas directly connected to the drainage system, whereas combined events also include flows from pervious surfaces. The classification was carried out using successive weighted least squared regression analysis of the observed runoff and rainfall events, removing combined events if the runoff exceeded the regression line by a given depth, the δc EIA criterion. The slope of the final regression line (which for EIA sourced events is fraction of the rainfall that produces runoff) is considered to be the event based separate sewer fraction (F_s) and the results are shown in Table 1.

2.5 Monthly rainfall runoff coefficients

The monthly rainfall-runoff coefficients were calculated for 20 urban and 5 rural catchments (Fig. 4, Table A.2), with the data from paired rural and urban catchments providing the basis for calculating the three fractions (F_s , F_c and F_p). In most catchments, the lowest monthly precipitation typically occurs in spring (March) and the highest in autumn (October). However, the highest monthly runoff coefficient values occur in winter (December-February) and the lowest values in summer (June-August), reflecting seasonal patterns of evaporation.

Fig 4. Monthly runoff coefficients for the five rural and 20 urban catchments

The important feature of the monthly runoff coefficient is that all the rural catchments have a similar response, whereas urban catchments show considerable variation between catchments. These differences are driven by the impervious fractions and the sewer network. Firstly, impervious areas increase the runoff coefficient in both summer and winter, but particularly in summer as the higher evaporation means there is a soil moisture deficit and consequently lower runoff in rural

catchments. Secondly, combined sewers reduce the runoff coefficient in both summer and winter due to the export of runoff to wastewater treatment plants. It is this large variation between the runoff coefficients that enables the three fractions (F_s , F_c and F_p) to be calculated.

2.6 Hydrological modelling

The separate sewer, combined sewer and pervious fractions (F_s , F_c and F_p) calculated in this work were used in a hydrological modelling study of three of the urban catchments (Fig. 2). These are the Ouseburn at Crag Hall (23016, our main case study catchment), Salmon Brook at Edmonton (38014, with low urban fraction), and Yeading West at Gutteridge Wood (39137, high urban fraction). They were selected as they cover a range of urban fractions. The purpose of this modelling is to establish whether inclusion of the three fractions (F_s , F_c and F_p) can reconcile errors in stream flow mass balance.

The Shetran hydrological model (Ewen et al. 2000, Birkinshaw et al, 2010) was selected for use here as it is physically-based and spatially-distributed, allowing explicit representation of the impervious areas. The model is usually applied to predominantly rural catchments (Birkinshaw et al. 2014; Birkinshaw et al. 2017) but it can take into account the different hydrological response within impervious and pervious areas. It includes components for vegetation interception and transpiration, overland flow, variably saturated subsurface flow and channel-aquifer interactions. Solutions to the governing, physics-based, partial differential equations of mass and momentum are achieved on a three-dimensional grid using finite-difference equations (<https://research.ncl.ac.uk/shetran/>).

To account for the sealing of the ground surface in impervious areas, the saturated conductivity is set to zero, preventing infiltration. To account for evaporation where there are separate sewers, 20% of the precipitation is removed and no additional evaporation is considered (see Section 3.2). 100% of the precipitation is removed in areas where there are combined sewers. A high Strickler (low roughness) overland flow parameter of $10 \text{ m}^{1/3} \text{ s}^{-1}$ is specified for impervious areas to take into account the effect of separate sewers, with rapid flow of water to and within the pipe network. The value selected is based on typical values obtained during previous calibrations of urban areas (Op de Hipt et al., 2017; Sreedevi et al., 2019).

A grid resolution of 100m was used for the smaller Salmon Brook at Edmonton (38014) and Yeading West at Gutteridge Wood (39137) catchments, and 200m for the larger Ouseburn at Crag Hall (23016) catchment (Fig. A.2). While this is still relatively coarse in relation to the highly

heterogeneous nature of the urban environment, it allows a more adequate spatial partitioning of the runoff than in lumped and semi-distributed hydrological models.

For the assessment of water balance, it is important to establish independence between the estimation of the sewer fractions and the modelling. Consequently, the modelling did not consider changes to the parameters controlling evaporation (Table A.4). The parameters were specified using an existing library of values that were developed for a UK national hydrological assessment (Lewis et al., 2018a). This library was also used to specify the soil properties (Table A.5).

For each catchment four different scenarios were simulated. Firstly, the existing urban area was classified as grassland, the predominant land cover in the catchment (scenario “NoUrb”). This provides a baseline simulation against which the impact of urbanisation can be assessed. Next, the urban areas were assumed sealed, drained by either all separate sewers (scenario “SS”) or all combined sewers (scenario “CS”). Fourthly, the separate and combined sewer fractions calculated in this work were used (scenario “SandC”).

For the Ouseburn at Crag Hall, the location of areas within the catchment containing separate and combined sewers are known, allowing the correct spatial distribution to be assigned in scenario “SandC”. For the other two catchments the locations are unknown. For these catchments, each grid square within the urban fraction is assumed to have both separate and combined sewers with the fraction of each depending on the value calculated in this work. Gridded 1km resolution hourly rainfall data (Lewis et al. 2018b) and daily potential evapotranspiration data were used (Robinson et al. 2016).

3. Method to calculate the separate sewer (F_s), combined sewer (F_c) and pervious (F_p) fractions

3.1 Development of the equations

The purpose here is to estimate F_s , F_c and F_p for a study catchment using monthly rainfall-runoff records. This considers a conceptual model of an urban catchment (Fig. 5), which corresponds to the left part of Fig. 1.

The areal fractions calculated by the model correspond to the area fractions by which the water reaches the catchment outlet, rather than the area fraction on which the precipitation falls. Runoff generated in fraction F_s reaches the catchment outlet via the sewer system/drainage network, while the contributions from F_p reach the catchment outlet via soil infiltration and channel-aquifer

interactions. Hence, an impervious area (e.g. a road) that drains to a previous area (a garden) is assigned to the F_p fraction, and similarly an area draining to a separate sewer system that is connected to a Sustainable Drainage Systems (SuDS) pond is also part of the F_p fraction. Areas of highly compressed soil are assigned as part of the F_s fraction and leakage from combined sewers (e.g. Minnig et al. 2018) is included as part of the F_p fraction.

Fig. 5. Schematic representation of an urban catchment. The three fractions correspond to the pathways by which the water reaches the catchment outlet or is exported from the catchment.

The following equations are applied on a calendar month basis (i.e. $t=1, \dots, 12$). Q (mm) is the long-term discharge, P (mm) is long-term catchment areal average precipitation and R is the runoff coefficient (0-1). The subscripts s , c and p denote separate sewers, combined sewers and pervious areas, respectively.

The estimated long-term monthly average discharge Q' at the catchment outfall comprises contributions from the three types depicted in Fig. 5:

$$Q'(t) = Q'_s(t) + Q'_c(t) + Q'_p(t) \quad (1)$$

The runoff from each area depends on the runoff coefficient of that area, the fraction of the catchment of that type and the precipitation:

$$Q'_s(t) = R_s * F_s * P(t) \quad (2)$$

$$Q'_c(t) = R_c * F_c * P(t) \quad (3)$$

$$Q'_p(t) = R_p * F_p * P(t) \quad (4)$$

Hence from Eqns. 1 -4:

$$Q'(t) = R_s * F_s * P(t) + R_c * F_c * P(t) + R_p * F_p * P(t) \quad (5)$$

Considering the separate sewer fraction (F_s), 80% of precipitation enters the drainage system, with a 20% loss to evaporation ($R_s=0.8$), see Section 3.2 for a discussion of this issue. Runoff entering the combined sewer network (F_c) is exported from the catchment and does not contribute to river discharge ($R_c=0$), except if the waste water treatment plant is located within the catchment, in which case it is assumed to be part of the separate sewer fraction. The runoff coefficient for the pervious area R_p is time varying (on calendar month basis) due to the seasonal variations in evaporation and subsurface storage, and the value is obtained from the analysis of rainfall-runoff records in a paired rural catchment:

Hence from Eqn. 5:

$$Q'(t) = 0.8 * F_s * P(t) + R_p(t) * F_p * P(t) \quad (6)$$

The sum of the three area fractions is equal to 1, therefore:

$$F_c = 1 - F_s - F_p \quad (7)$$

There are 12 simultaneous equations (Eqn. 6) that provide the 12 monthly estimates of long-term average discharge (Q'), for which the 12 observed monthly long-term average discharges are available (Q). Hence, for each catchment there are two unknowns, F_s and F_p , which are numerically estimated by minimising the residuals between long-term average estimated $Q'(t)$ and observed $Q(t)$. F_c is then obtained from Eqn. 7.

In some catchments an additional term is required in Eqn. 6 to account for effluent inputs from waste water treatment plant for household waste water sourced from outside the catchment, adding an additional term to the equation, where $E(\text{mm})$ is the monthly effluent input:

$$Q'(t) = 0.8 * F_s * P(t) + R_p(t) * F_p * P(t) + E \quad (8)$$

According to NRFA, nine of the 20 urban catchments have significant augmentation from effluent inputs. These effluent flows were estimated here by extracting the minimum recorded daily discharge from hydrographs (noting that none of these catchments are baseflow dominated).

An example of the calculation of F_s , F_c and F_p for the Ouseburn case study catchment can be seen in Appendix A3.

Once the calculation of the three fractions (F_s , F_c and F_p) has been completed, the values can be used to improve the hydrological modelling of the catchment, with the methodology shown in Fig. 1.

3.2 Discussion of the method

A discussion of several aspects of the model development is considered in more detail in this section.

Firstly, the rural catchments were selected on the basis that they had low TIA values. However, all the rural catchments do have impervious areas (e.g. Table 1 shows a range of 3% - 7% of catchment area using OSMM). It was simply assumed that half the impervious fraction contributed to separate sewers and half to the combined sewers. (Sensitivity tests indicated that the estimates of the separate and combined sewer fractions were insensitive to this assumption.)

Secondly, it is assumed that depression storage, which is subsequently lost to evaporation, is relatively small in urban areas. The model assumes that this evaporation loss is 20% of the precipitation falling in areas with separate sewers and the remaining 80% contributes to flow at the catchment outlet. Losses to evaporation are difficult to quantify, with a wide range of values given in the literature (Mansell and Rollet, 2006; Redfern et al., 2016). For roofs, Ragab et al. (2003a) estimated evaporation losses of 13 to 56% of precipitation, depending on the orientation and the slope. For four car parks and roads located in the south of England, Ragab et al. (2003b) found that 21-24% of the annual precipitation evaporated and Ramier et al. (2011) found that annually 10% of the precipitation evaporated in the city of Nantes in north-west France. Contradictory seasonal patterns were found by Hollis and Ovenden (1988) and Ragab et al. (2003b). Hence, a constant loss of 20% of precipitation to evaporation is a reasonable central estimate. Sensitivity tests with losses in the separate sewer fraction of both 0% and 40% of precipitation are considered in Section 4.4.

Thirdly, the soils in the pervious areas within the urban catchments were assumed to have the same runoff coefficients as those in the rural catchments. It has been demonstrated that building activity within the urban environment produces compacted soils with low permeability and reduced infiltration (Gregory et al., 2006; Chen et al., 2014; Fletcher et al., 2013). However, similar issues of

compaction exist in the rural catchments. For example, stock grazing and traffic loading in agricultural areas can cause compaction, enhancing surface runoff (Alaoui et al., 2018). Conversely, well-established urban gardens/parks within an urban catchment can have high permeability and infiltration rates (Bartens et al., 2008; Woltemade, 2010; Redfern et al., 2016). This complex issue of accounting for soil heterogeneity is an outstanding issue for hydrology modelling in general. It is suggested that further work is carried out to assess the effect of this assumption.

Fourthly, it is assumed the sewer network boundaries do not cross the surface water catchment boundaries, which is not always the case. For example, there can be parts of the separate sewer network outside a surface catchment boundary which flow across the surface water divide to the catchment outlet, so producing higher flows than expected (Vrebos et al., 2014). Similarly, there can be a reduced flow at the catchment outlet if the separate sewer network drains into an adjacent catchment. This is an issue for other approaches, such as the calculation of the separate sewer fraction using the event-based rainfall-runoff response, which also uses the catchment runoff. In order to quantify these additional flows or losses, details of the sewer network topology are required.

4 Results and Discussion

4.1 Verification of the F_s and F_c fractions with the TIA

The separate (F_s) and combined (F_c) sewer values estimated using Eqn. 8 are provided for each urban catchment in Table 1. The sum of F_s and F_c is a measure of the impervious area, but is not equal the TIA as it only includes the area fraction that flows into the sewer network. (Note, the TIA values are generated independently of those derived from Eqn. 8). In Fig. 6a, for each urban catchment the calculated $F_s + F_c$ value is plotted against the TIA derived from the LCM 2007 data and the OS MasterMap data set, assuming gardens respond as either pervious areas or impervious areas (i.e. OSMM and OSMM+, respectively). The line of equality shows that, for most catchments, the calculated $F_s + F_c$ falls between these lower and upper estimates of TIA, as would be expected, i.e. between the limits in which all gardens are assumed as either permeable or impermeable. For example, in the Ouseburn at Crag Hall catchment (23016) the $F_s + F_c$ value is 0.30 and the lower and upper estimates of TIA are 0.25 and 0.41. However, for the less urbanised catchments the calculated impervious fraction in five of the 20 catchments were slightly lower than the TIA value where all gardens were assumed pervious (OSMM). This indicates that there may be parts of the catchment classified as impervious that are not hydraulically connected to the drainage network. For example, farm buildings, tracks and small roads classified as impervious in the OSMM data set, but which

drain to pervious areas. For the highly urbanised catchments the calculated impervious fraction approaches the corresponding TIA value that assumes all gardens as impervious (OSMM+). The maximum impervious fraction ($F_s + F_c$) calculated is 0.62 (ID 39137) for a catchment in London with the OSMM value of 0.35 and an OSMM+ value of 0.7. This suggests that most of the gardens in the catchment act as impervious areas and are hydraulically connecting to the drainage network. Google areal images and Google Street View shows that the vast majority of houses in this catchment have converted their front gardens into paved areas to allow for car parking, but most of the houses still have 'green' rear gardens. One possible explanation, as discussed previously, is that many of these gardens have highly compacted soils which are acting as impervious areas. Alternatively, roadside verges, urban parks and school fields classified as pervious in the OSMM dataset, are acting as impervious areas. In general, it seems that the hydraulic connectivity of the urban part of a catchment increases as the urban fraction increases.

Fig. 6. a) Comparison between the calculated separate (F_s) plus combined (F_c) sewer fractions for the 20 urban catchments and the corresponding observed TIA calculated using three different methods (in OSMM the gardens are assigned to the pervious fraction and in OSMM+ the gardens are assigned to the impervious fraction). b) Comparison for nine catchments between the separate sewer fractions (F_s) calculated in this work using monthly runoff coefficients and using the event-based approach (there are two values at 0.11, 0.12). The line of equality is shown in both a) and b).

4.2 Verification using the event-based rainfall runoff

The separate sewer fraction (F_s) for the 20 urban catchments are provided in Table 1. The separate sewer fraction has been verified against the corresponding fraction calculated using the event-based rainfall runoff approach for nine catchments (see Section 2.4) where hourly observed discharge data were available. For the Ouseburn at Crag Hall case study catchment the separate sewer fraction (F_s) calculated using the event based rainfall-runoff method is 0.12, which is very similar to the value of F_s of 0.11 calculated in this work using the monthly runoff coefficients. Similarly, the other eight catchments all show excellent correspondence (Fig. 6b). The largest difference is for Eastwood Brook at Eastwood catchment (ID = 37033) where F_s calculated using the event-based rainfall-runoff approach is 0.22 and the F_s calculated in this work is 0.18. There is some evidence of the sewer network crossing the surface water catchment boundary in this catchment (see Section 3.2) and this could account for the difference. Overall, it is encouraging that the derived values agree so well, despite being calculated using different methodologies.

4.3 Verification using the sewer network

For the majority of the study catchments, there are no accurate details about the presence of separate or combined sewers. However, details of the sewer network for the Ouseburn at Crag Hall case study catchment (23016) have been published (Newcastle City Council, 2015) and are shown in Fig. 3, allowing verification of the separate sewer fraction to be carried out.

Table 1 shows the calculated percentage of the impervious area that is drained by separate sewers is 37% (F_s is 0.11 and F_c is 0.19, hence the fraction is $0.11/0.30$), while the corresponding figure measured using information from the Newcastle City Council report gives a slightly higher value of 39%. However, in a few housing estates there are separate sewers which feed into combined sewers in the downstream network, which has not been accounted for in Fig. 3. Hence, the value of 39% provides an upper estimate of the separate sewer fraction.

4.4 Sensitivity tests with different evaporation losses

The previous results have all assumed that depression storage, which is subsequently lost to evaporation, is 20% of the annual precipitation. Sensitivity tests were carried out with evaporation losses in the separate sewer fraction of both 0% and 40% of precipitation. The result of these changes had a minor impact on the impervious fraction ($F_s + F_c$) value, but it did change the proportions of the separate sewer fraction (F_s) and the combined sewer fractions (F_c). Lower evaporation reduced the separate sewer fraction, F_s (and hence increased the combined sewer

fraction, F_c), with higher evaporation increasing the separate sewer fraction, F_s . (Note, for the pervious part of the catchment, evaporation is accounted through the use of the runoff coefficient from the paired rural catchment).

4.5 Hydrological modelling

The results of the hydrological modelling of three catchments under the four different scenarios are shown in Table 3. For the assessment of water balance, it is important to establish independence between the estimation of the sewer fractions and the modelling. Consequently, the modelling did not consider changes to the parameters controlling evaporation. Soil parameters were also not altered except the surface soil saturated hydraulic conductivity, which was calibrated to improve the quality of the hydrograph recessions (Table A.5). For example, for the Yeading West at Gutteridge Wood (39137) catchment the saturated conductivity was reduced to 6m/day, which produced peakier flows and a steeper recession but did not affect the overall water balance.

Table 3. Hydrological modelling results. NSE is the Nash Sutcliffe Efficiency and PBias is the percentage bias in the outlet discharge. ¹ the results are for hourly discharge data. ² the results are for daily discharge data. Four scenarios are considered. “NoUrb” sets the entire urban area to grass with no sewers considered, “SS” the impervious area is simulated entirely with separate sewers, “CS” the impervious area is simulated entirely with combined sewers. “SandC” uses separate and combined sewers calculated in this work.

Catchment Name	Area (km ²)	Separate sewer fraction, F_s	Combined sewer fraction, F_c	Pervious fraction, F_p	NoUrb		SS		CS		SandC	
					NSE	PBias	NSE	PBias	NSE	PBias	NSE	PBias
Ouseburn at Crag Hall (23016) ¹	53.8	0.11	0.19	0.70	0.60	+11.6	0.08	+84.1	0.45	-52.5	0.89	-1.0
Salmon Brook at Edmonton (38014) ²	22.8	0.14	0.01	0.85	0.55	-37.9	0.82	+2.0	0.55	-51.2	0.82	+0.1
Yeading West at Gutteridge Wood (39137) ²	17.9	0.29	0.33	0.38	0.11	-27.4	-0.12	+84.6	0.04	-67.1	0.77	+1.1

For the Ouseburn catchment in scenario “NoUrb”, where all urban areas are classified as grassland, the simulated discharge is higher than the observed discharge (PBias = +11.6%) and the Nash Sutcliffe Efficiency (NSE) is 0.6. For scenario “SS”, where all sewers are considered as separate, the PBias is 84.1%, demonstrating the overestimation in runoff due to sealed surfaces. In scenario “CS”, where sewers are considered combined, there is a significant underestimation in discharge due to the export of runoff (PBias=-52.5%). For scenario “SandC”, using the fractions of separate and combined sewers calculated in this work the PBias is -1.0% and the NSE is 0.89. Fig. 7a shows a comparison of the hydrographs for scenarios “NoUrb” and “SandC” for the calendar year 2008. Runoff is significantly underestimated in scenario “NoUrb” under dry antecedent conditions (e.g. June 2008). The introduction of sealed surface and sewers in scenario “SandC” remedies this shortcoming. Under wetter winter conditions (Sept –Dec 2008), the recessions are too gradual and the base flow is too high in scenario “NoUrb”, whereas these features are adequately simulated in scenario “SandC”. In Fig. 7b, a 30-day section over August is shown for all four scenarios. Each event shows that in Scenario “SS” separate sewers significantly increase the discharge and in Scenario “CS” combined sewers significantly reduce the discharge.

Fig. 7. Hydrological Modelling Simulation Results for the OuseBurn Crag Hall Catchment (ID 23016).

a) all of 2008 b) a section from 31/7/2008 to 30/8/2008. The simulation was carried out from 1/1/1990 to 31/12/2014.

Considering all three catchments shown in Table 3, the highest NSE and the lowest PBias values are all attained when the sewer fractions calculated in this work are applied. However, it is noted that the NSE values for Salmon Brook (ID 38014) are very similar under scenarios “SS” and “SandC”, which is due to the separate sewer fraction (F_s) accounting for 95% of impervious area ($F_s + F_c$). For the Yeading West catchment (ID 39137), the NSE under scenario “SandC” was 0.77, which is significantly higher than the values attained for the other scenarios. This is the most urbanised of the three catchments considered ($F_s + F_c = 0.62$), with the separate sewer fraction accounting for 46% of the impervious area ($F_s + F_c$), hence the extreme assumptions under scenarios “SS” and “CS” are poor.

In hydrological modelling, the error between the observed and simulated outlet discharges are generally corrected during calibration through parameter compensation (Salvadore et al. 2015). In particular, the calibration of the parameters that affect the actual evaporation is often performed to correct for errors in the overall water balance (Guerreiro et al. 2017). Although this can produce good correspondence between the measure and simulated discharge, it is not satisfactory; as Beven (2019) states “getting good results for the wrong reasons can be misleading when we want to simulate the impacts of change”. The hydrological modelling has demonstrated the importance of incorporating the correct fractions of separate and combined sewers, to avoid the need to calibrate the water balance. Hence, the model is getting the “right answers for the right reasons” (Kirchner, 2006).

Future work is planned on conducting hydrological modelling of the remaining catchments and assessing the effect of different spatial resolutions and the spatial locations of the separate and combined sewer fractions.

5. Conclusions

Hydrological models of urban and peri-urban catchments are often used by flood risk managers and planners in to help inform decision making. However, the models are generally limited by a lack of knowledge of the urban runoff processes within the catchments. In this work a novel method to calculate the separate sewer fraction, combined sewer fraction and a pervious fraction has been developed and applied to 20 urban river catchments. The method makes use of monthly runoff coefficients from an urban and a paired rural catchment and the algorithm is simple to implement. As the data requirements for this method are only the more readily available long term monthly rainfall-runoff records, it is particularly useful in catchments which do not have freely available

sewer topology data or fine resolution hydrological time-series data, which makes alternative methods impossible to apply. To verify the method, the derived fractions were compared against map data and the standard method, which utilises hourly data. The results showed excellent correspondence.

Hydrological modelling was carried out for three catchments, partitioning the sewer network into a separate sewer fraction, which flows into the drainage network, and a combined fraction, which is removed from the catchment. The model was parameterised using an existing library of parameter values. Good agreement between the observed and simulated outlet hydrographs was achieved, and the volume of simulated flows were in very close correspondence to the observed. Scenarios simulated by converting the urban areas to grassland and partitioning the sewer network into either all separate or all combined sewers all gave less good simulations and, in most cases, very poor simulations and large errors in the hydrological mass balance. It is therefore recommended that prior to the application of detailed hydrological models for urban areas, the simple approach developed in this study is applied.

Two recent modifications to existing urban environments have the potential to cause considerable changes to the pervious and impervious fractions. Replacing pervious gardens with parking spaces (Warhurst et al., 2014; Kelly, 2018) will significantly increase the impervious fraction. On the other hand, the increased use of SuDS and green infrastructure (O'Donnell et al., 2020) will increase the infiltration and hence reduce the impervious fraction. The method developed in this work, in conjunction with hydrological modelling, provides a powerful means for initial quantification of the impacts of such changes on urban runoff and flooding.

Overall, we believe that this work provides an insight into the hydrological response of typical urban catchments where detailed sewer and hydrological data is not available. It takes into account both land use and sewerage factors, thereby providing a solid basis to further analyse and model improved design and management of flood and quality issues.

Acknowledgements

This work was carried out as part of the EPSRC funded Urban Flood Resilience project (EP/P004334/1). Paul Quinn and Russell Adams are thanked for their discussions about the hydrology and water quality issues in the Ouseburn case study catchments. Three anonymous

reviewers are also thanked for their insightful comments that have resulted in a much improved and comprehensive paper.

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Appendix

A1. Details of Land Use Classification and the Total Impervious Area (TIA)

An example of the assignment of land-use types is provided in Fig. A.1 for a suburban area within the Ouseburn case study catchment at Crag Hall. The Google Earth image in Fig. A.1a shows the patchwork of buildings, roads and gardens. In Fig. A.1b the gardens are assigned to the pervious fraction (OSMM) and in Fig. A.1c the gardens are included in the impervious fraction (OSMM+). To the south of the images in region 1 there are detached and semi-detached houses with large gardens that would ideally be included in the pervious fraction. Alternatively, in region 2 there are terraced houses with paved gardens which should be included in the impervious fraction. However, the OS MasterMap layer assigns all residential gardens to the same make class (General Surface; Multiple – see Table A.1) It would be expected that the actual TIA would fall somewhere between the lower and upper limits provided by OSMM and OSMM+. The LCM dataset, Fig. A.1d, classifies almost this entire area as either urban/suburban. Region 1, with large gardens, is assigned as suburban and region 2, with terraced houses, as urban.

Table A.1 Extracted land use data from the OSMM Topography Layer. * is the data type used in the OSMM Topography layer to specify gardens and it can be classed as either pervious or impervious

Descriptive Group	Make	Extracted land use data
Building	All makes	Impervious
Roadside	Manmade	Impervious
	Multiple	Pervious
	Natural	Pervious
Road or Track	All makes	Impervious
General Surface	Manmade	Impervious
	Multiple*	Pervious/ Impervious
	Natural	Pervious
Natural Environment	All makes	Pervious

Fig. A.1 Part of the Ouseburn at Crag Hall case study catchment. a) Google Earth image (© Google, digital Globe), b) OS MM built-up area with gardens pervious (OSMM), c) OS MM built-up area with gardens impervious (OSMM+), d) LCM 2007 image

A2. Details of the monthly runoff coefficients for the five rural and 20 urban catchments

Table A.2. Monthly runoff coefficients for the five rural and 20 urban UK catchments, separated out in relation to the nearest urban conurbation. Rural catchments in bold.

Nearest city	Catchment number	Catchment name	Month											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Birmingham	54096	Hadley Brook at Wards Bridge	0.51	0.51	0.47	0.30	0.21	0.17	0.16	0.13	0.16	0.16	0.31	0.43
	28003	Tame at Water Orton	0.58	0.6	0.63	0.53	0.46	0.45	0.44	0.41	0.44	0.4	0.48	0.54
	28039	Rea at Calthorpe Park	0.53	0.52	0.5	0.41	0.33	0.32	0.32	0.27	0.32	0.32	0.41	0.48
	28066	Cole at Coleshill	0.43	0.43	0.42	0.34	0.25	0.26	0.25	0.2	0.23	0.23	0.32	0.39
	54063	Stour at Prestwood Hospital	0.55	0.59	0.58	0.47	0.39	0.39	0.41	0.34	0.37	0.35	0.47	0.51
Leeds	27064	Went at Walden Stubbs	0.54	0.53	0.50	0.33	0.23	0.20	0.19	0.16	0.20	0.22	0.34	0.43
	27081	Oulton Beck at Farrer Lane	0.47	0.45	0.43	0.31	0.24	0.22	0.19	0.18	0.18	0.2	0.28	0.37
London	37011	Chelmer at Churchend	0.55	0.56	0.45	0.28	0.17	0.09	0.07	0.06	0.06	0.15	0.27	0.42
	37018	Ingrebourn at Gaynes Park	0.63	0.67	0.61	0.41	0.32	0.23	0.24	0.18	0.19	0.27	0.37	0.52
	37019	Beam at Bretons Farm	0.55	0.56	0.48	0.35	0.27	0.23	0.23	0.19	0.2	0.26	0.32	0.44
	37031	Crouch at Wickford	0.46	0.48	0.35	0.28	0.2	0.14	0.14	0.13	0.13	0.2	0.28	0.39

	37033	Eastwood Brook at	0.41	0.42	0.39	0.32	0.26	0.2	0.21	0.22	0.21	0.27	0.28	0.36
		Eastwood												
	38007	Canons Brook at Elizabeth	0.62	0.63	0.58	0.47	0.35	0.29	0.29	0.25	0.26	0.34	0.41	0.54
		Way												
	38014	Salmon Brook at Edmonton	0.63	0.59	0.51	0.34	0.27	0.19	0.16	0.15	0.17	0.27	0.36	0.5
	38022	Pymmes Brook at	0.67	0.67	0.69	0.51	0.46	0.39	0.38	0.36	0.37	0.42	0.47	0.58
		Edmonton												
		Silver Street												
	39049	Silk Stream at Colindeep	0.54	0.56	0.54	0.4	0.31	0.28	0.26	0.23	0.26	0.28	0.37	0.46
		Lane												
	39092	Dollis Brook at Hendon	0.57	0.53	0.53	0.36	0.25	0.21	0.18	0.17	0.19	0.28	0.37	0.48
		Lane Bridge												
	39131	Brent at Costons Lane	0.54	0.52	0.51	0.38	0.33	0.27	0.26	0.25	0.25	0.33	0.39	0.48
		Greenford												
	39137	Yeading West at Gutteridge	0.48	0.48	0.45	0.32	0.33	0.33	0.3	0.31	0.24	0.29	0.37	0.45
		Wood												
Manchester	68020	Gowry at												
/Liverpool		Bridge	0.57	0.52	0.49	0.34	0.20	0.23	0.20	0.20	0.21	0.24	0.38	0.51
		Trafford												
	69013	Sinderland Brook at	0.61	0.61	0.62	0.45	0.39	0.31	0.29	0.28	0.29	0.35	0.48	0.54
		Partington												
	69030	Sankey Brook at Causey	0.83	0.75	0.74	0.55	0.44	0.39	0.41	0.41	0.43	0.51	0.68	0.73
		Bridges												
	69032	Alt at Kirkby	0.72	0.68	0.67	0.52	0.43	0.41	0.42	0.38	0.4	0.46	0.59	0.65
Newcastle	23018	Ouseburn at	0.53	0.49	0.38	0.37	0.20	0.16	0.12	0.14	0.19	0.21	0.35	0.44
		Woolsington												
	23016	Ouseburn at Crag Hall	0.45	0.42	0.37	0.33	0.21	0.16	0.16	0.17	0.2	0.21	0.3	0.41

A3. Worked example for the calculation of the separate sewer (F_s), combined sewer (F_c) and pervious (F_p) fractions

To illustrate the calculations of F_s , F_c and F_p consider the Ouseburn case study catchments (Section 2.1) where the fractions are calculated for the urban Crag Hall catchment (Table A.3). The estimated discharge (Q') for each calendar month depends on the long-term monthly precipitation (P), the runoff coefficient (R_p) for the paired rural Ouseburn at Woolsington catchment (ID 23018), the effluent input (E), and the separate sewer fraction (F_s) and pervious fraction (F_p) of total catchment area. For example, in January the monthly precipitation (P) is 49.2mm, the runoff coefficient (R_p) is 0.526, the effluent input is 0, and hence from Eqn. 8 the estimated discharge is:

$$Q'(\text{mm}) = 0.8 * F_s * 49.2 + 0.526 * F_p * 49.2 + 0 \quad (\text{A1})$$

Therefore,

$$Q'(\text{mm}) = 39.36 F_s + 25.88 F_p \quad (\text{A2})$$

and the observed long-term average monthly discharge (Q) for January is 22.3mm. The two unknown values (F_s and F_p) are estimated by minimising the sum of the absolute residuals between the estimated discharge (Q') and the observed discharge (Q) for the twelve simultaneous equations (one for each month). This solution provides a value of F_s of 0.109 and F_p of 0.696 (hence from Eqn. 7 F_c is 0.195).

Table A.3 Calculation of the separate sewer fraction, F_s (0.109), and the pervious fraction, F_p (0.696), for the Ouseburn at Crag Hall catchment in Newcastle upon Tyne. An estimated discharge (Q') is defined for each month (Eqn. 8). Then F_s and F_p are calculated by minimising the error between the estimated discharge (Q') and the actual discharge (Q) for the 12 simultaneous equations ($F_c = 1 - F_s - F_p$).

Month	P Precipitation (mm)	R Runoff Coefficient from rural catchment 23018 (-)	Q' Estimated Discharge (mm), calculated from Eqn 8	Q' Final Estimated Discharge (mm)	Q Actual Discharge (mm)	Absolute Error (mm)
Jan	49.2	0.526	$39.36 F_s + 25.88 F_p$	22.3	22.3	0.0
Feb	46.9	0.485	$37.52 F_s + 22.75 F_p$	19.9	19.6	0.3
Mar	38.7	0.369	$30.96 F_s + 14.28 F_p$	13.3	14.4	1.1
Apr	54.4	0.352	$43.52 F_s + 19.15 F_p$	18.1	18.2	0.1
May	50.3	0.168	$40.24 F_s + 8.45 F_p$	10.2	10.7	0.5
Jun	64.9	0.124	$51.92 F_s + 8.05 F_p$	11.3	10.5	0.8
Jul	60.5	0.081	$48.40 F_s + 4.90 F_p$	8.7	9.7	1.0
Aug	71.0	0.111	$56.80 F_s + 7.88 F_p$	11.6	11.7	0.1
Sep	60.4	0.163	$48.32 F_s + 9.85 F_p$	12.1	12.3	0.2
Oct	66.1	0.180	$52.88 F_s + 11.90 F_p$	14.1	13.7	0.4
Nov	73.2	0.336	$58.56 F_s + 24.60 F_p$	23.5	21.6	1.9
Dec	61.2	0.430	$48.96 F_s + 26.32 F_p$	23.6	25.1	1.5

A4. Hydrological Modelling Details

a) Ouseburn at Crag Hall (23016)

b) Yeading West at Gutteridge Wood (39137)

c) Salmon Brook at Edmonton (38014)

Fig. A.2 Shetran grid network, elevations, and river channels for the three catchments for which hydrological modelling was carried out.

Table A.4 Vegetation parameters in pervious areas used in the Shetran simulations. The canopy drainage parameter, C_k , is the rate of drainage when the canopy is at its storage capacity and C_b is used in an exponential function to describe how the drainage rate falls as the canopy. The actual/potential evaporation is the value at field capacity, in the model it decreases with soil moisture tension.

Parameter	Arable	Forest	Grass
Canopy drainage – C_k (mm/s)	1.4E-5	1.4E-5	1.4E-5
Canopy drainage – C_b (mm ⁻¹)	5.1	5.1	5.1
Canopy storage (mm)	1.0	5.0	1.0
Rooting depth (m)	0.8	2.0	1.0
Leaf area index (–)	2.0	5.0	3.0
Actual/potential evaporation (–)	0.8	1.0	0.8
Strickler overland flow (m ^{1/3} s ⁻¹)	1.0	0.5	1.0

Table A.5 Soil parameters in pervious areas used in the Shetran simulations. K_{sat} is the saturated conductivity which has been calibrated for the surface soil in each catchment. The remaining parameters were not calibrated.

	23016	23016	38014	38014	39137
Parameter	Surface Soil	Sub Soil	Surface Soil	Sub Soil ^a	Surface Soil ^b
K_{sat} (m/day)	30.0	1.0	50.0	2.0	6.0
Saturated water content (–)	0.403	0.403	0.403	0.403	0.439
Residual moisture content (–)	0.025	0.025	0.025	0.025	0.010
Van Genuchten alpha (m ⁻¹)	3.83	3.83	3.83	3.83	3.14
Van Genuchten n (–)	1.37	1.37	1.37	1.37	1.18
Depth at base of layer (m)	0.4	2.0	0.6	1.4	1.0

^a 36% of the 38014 catchment has an active sub soil

^b in catchment 39137 there is no active sub soil