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

James D. Miller [a,*], Hyeonjun Kim [b], Thomas R. Kjeldsen [c], John Packman [a], Stephen Grebby [d], Rachel Dearden [d]

[a] Centre for Ecology and Hydrology (CEH), Maclean Building, Crowmarsh Gifford Oxfordshire OX108BB, United Kingdom
[b] Water Resources & Environment Research Department, Korea Institute of Construction Technology, Daewa-Dong 283, Goyangdae-Ro, Ilsanseo-Gu, Goyang-Si, Gyeonggi-Do 411-712, South Korea
[c] Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, United Kingdom
[d] British Geological Survey (BGS), Environmental Science Centre, Keyworth, Nottingham NG12 5GG, United Kingdom

SUMMARY

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

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

1. Introduction

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

* Corresponding author. Tel.: +44 1491692708.
E-mail addresses: millj@ceh.ac.uk (J.D. Miller), hjkim@kict.re.kr (H. Kim), t.r.kjeldsen@bath.ac.uk (T.R. Kjeldsen), jcp@ceh.ac.uk (J. Packman), stgrebby@bgs.ac.uk (S. Grebby), rach1@bgs.ac.uk (R. Dearden).

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

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

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

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

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

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

2. The study area

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

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

The Rodbourne (ROD) catchment contains a highly urbanized area along the Rodbourne stream receiving runoff from central commercial and industrial areas along with pockets of dense suburban housing. The monitored part of the Rodbourne catchment (Area 5.5 km^2) represents an area that has been extensively developed since before $c \sim 1960$ and includes areas of combined foul and surface water drainage, where storm flows are conveyed to a major sewage treatment works that discharges into the main River Ray catchment. This treatment works contains storage to accommodate moderate storm flows from areas of central Swindon that can bypass the monitored site during high flows, however no
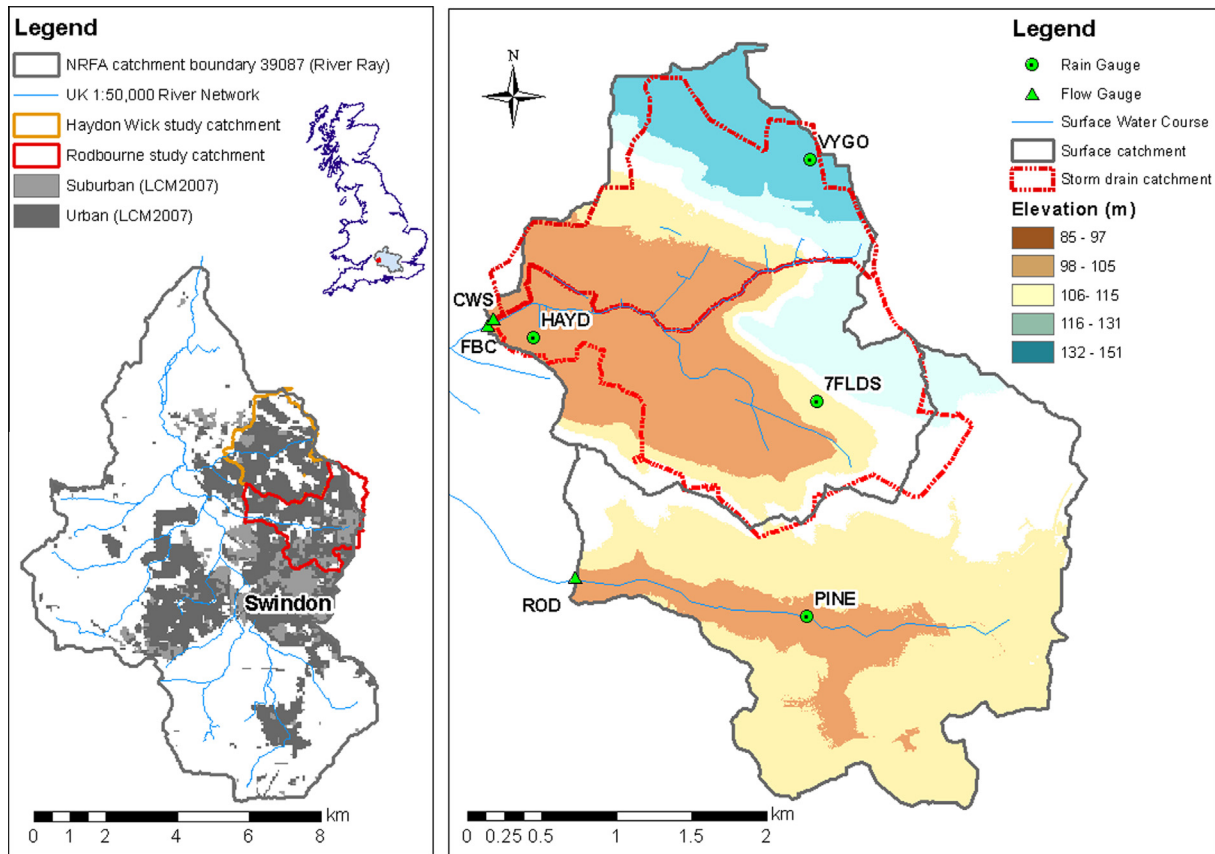
Fig. 1. Maps showing (left) urban extent derived from LCM2007 across the River Ray catchment (NRFA number 39087) and location relative to the wider and Thames Basin catchment (insert); (right) elevation and apparatus and boundaries of surface and modified storm water catchment with location of monitoring sites. The borders of the storm water catchments do not directly correspond to the surface catchments derived from a DTM as they follow artificial drainage pathways.

precise data on these flows are available (Howard Humphreys, 1986; Thames Water *pers comms*).

The Haydon Wick (HW) catchment contains a peri-urban area of development built on a previously rural area draining to the Haydon Wick brook. The catchment contains a mixture of housing and commercial developments built at various stages before and since *c* ∼ 1960, but is dominated by large-scale peri-urban housing and commercial expansion developed since the 1990s. The area has suffered from historical localized flooding since early development (Howard Humphreys, 1986) and severe flooding in 2007 hastened the call for additional flood alleviation works (EA, 2008). The introduction of major storm drainage systems in the early 2000s to the north of the catchment has significantly altered natural catchment pathways and the modified contemporary catchment boundary (Fig. 1) has therefore been defined using storm-drainage network maps.

Monitoring of the Haydon Wick catchment captures flow leaving the catchment at two parallel locations on the eastern side of the catchment, as shown in Fig. 1. The storm-drain location (CWS) monitors flow routed via a major storm-drain system draining surface runoff of the northern HW catchment (2.11 km^2). The natural channel site of HW brook is monitored within a culvert (FBC) and monitors flows received from both permeable and impermeable areas to the south (3.07 km^2). The flows from both locations (CWS and FBC) combine further down the catchment before joining the Ray, but the presence of significant floodplain storage meant it was not practical to gauge flows downstream of the selected sites. Prior to storm drainage systems being installed in the northern areas (∼2002), the catchment drained

entirely into the Haydon Wick brook and through the FBC culvert location.

3. Instrumental setup

Monitoring of key hydrological parameters was undertaken throughout the period from May 2011 to October 2012. This section details the measurements taken and the processing applied to derive good quality data.

3.1. Potential evapotranspiration

Measurements of diurnal variation in latent heat flux were obtained during the period May 2011 to April 2012 from an eddy covariance mast installed in a residential garden located within a peri-urban area of housing (Ward et al., 2013). The median diurnal latent heat flux for each month over the observed period were used to derive the total monthly evaporation. Additional data covering the monitoring period and onwards to October 2012 were obtained from the Met Office Rainfall and Evaporation Calculating System (MORECS) that provides monthly values for meteorological variables across the entire UK on a 40 km^2 grid. The study area is located to the eastern edge within MORECS grid square 158, containing a large area of vegetation along with the urban areas of Swindon. Measured local suburban evaporation during the period May 2011 to April 2012 revealed that actual evaporation was on average 60% of the MORECS value. This factor was then applied to the MORECS data on potential evapotranspiration (PET) for the

remaining period to October 2012 to provide the most accurate monthly values for PET over the full monitoring period.

3.2. Rainfall monitoring

Rainfall was measured over the monitoring period using four tipping bucket (0.2 mm) raingauges located within the two selected catchments (Fig. 1). The gauges were positioned in suitably exposed locations with ease of access and free from vandalism. Not all gauges were operational over the entire study period due to instances of blockage and malfunction, however, the quantity of rainfall measured across the four sites was consistent when operational (Fig. 2). A single time series of mean 15 min catchment average rainfall was derived using quality controlled data from across the four sites.

3.3. Soil properties

Soil samples taken across the Swindon area by the British Geological Survey were analysed through particle size analysis for clay, sand and silt content, and using loss-on-ignition (LOI) methods to determine total soil organic matter (SOM). Soils were found to vary considerably between sandy loams in higher areas in the north to silty clay loams in lower areas to the south. The characteristics of the physical soil samples were subsequently used to determine a number of associated hydrologically relevant soil properties for each catchment through the application of pedo-transfer functions (PTFs), including: bulk density (Alexander, 1980), saturated porosity (Mayr and Jarvis, 1999), saturated hydraulic conductivity (Wostern et al., 1999), and field capacity (Hall et al., 1977). Drilled soil pits undertaken across the study area indicated a variety of soil depths across the study area with an average depth of 0.36 m (n = 93). During 2011 soils were particularly dry with high soil moisture deficits, while continuous wet weather in the latter part of 2012 saw soil moisture deficit values stay low (Marsh et al., 2013).

3.4. Flow monitoring

Flow gauging locations and characteristics are summarised in Table 1 with their respective locations illustrated in Fig. 1. At each location flow was monitored using a Starflow™ ultrasonic doppler instrument, recording velocity and depth at a 1 min resolution. Rating curves were developed from observed data where possible using velocity-area relationships to transform depth and velocity into a 15 min time series of flow at each site, each rating curve validated by spot gauging. The Rodbourne gauge (ROD) is located within a box culvert of dimensions 2.4×1.6 m and situated on a false bed of paving slabs to provide an even base. The northern gauge in Haydon Wick (CWS) is located on the base of a box storm-drain of dimensions 3.6×1.5 m (only accessible through a manhole cover). The southern gauge in Hayden Wick (FBC) is located inside a circular culvert of diameter 1.8 m subject to heavy siltation – requiring the positioning of the instrument on top of a bespoke solid artificial concrete bed.

4. Historical change in urban extent and impervious cover

Due to a lack of historical remotely sensed imagery, long-term changes in urban land use and imperviousness for each decade during the period 1960–2010 were derived from topographic maps using the methodology developed by Miller and Grebby (2014). Firstly, digital topographic maps for each decadal interval were processed so that the abundance of artificial features within each 50 m grid cell was computed as a measure of the level of development. Grid cells were subsequently classified as either (i) rural (little or no development), (ii) suburban (urban areas of mixed development and green space), or (iii) urban (urban areas of near continuous development with little vegetation) to generate a 50 m land use map for each decade. These classifications are aligned to those developed and applied in the United Kingdom Land Cover Mapping products (Fuller et al., 2002). A land use change trajectory was applied to ensure consistency in the land
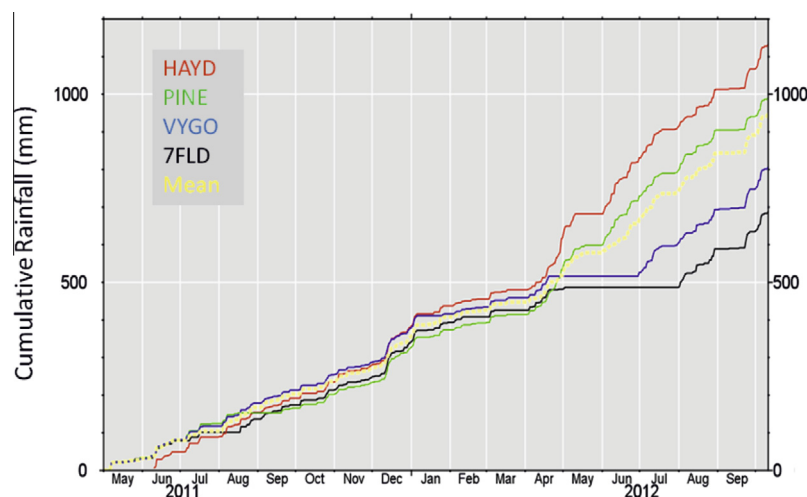
Fig. 2. Cumulative monthly rainfall across monitoring sites.

Table 1
Flow gauging locations and characteristics.

Gauge	Location	Watercourse	Catchment area (km²)	Data availability
CWS	Storm drain	Storm drainage – north Haydon Wick	2.11	2011/03/30 – 2012/10/16
FBC	Culvert	Haydon Wick brook	3.07	2011/03/30 – 2012/10/16
ROD	Culvert	Rodbourne stream	5.51	2011/05/09 – 2012/10/16

use mapping throughout the entire time-series. Decadal impervious cover estimates were then derived based on the catchment urban extent, *URBEXT*, as used in the UK Flood Estimation Handbook (IH, 1999) as an index of urban extent. The index *URBEXT* is a weighted sum of contributions from the suburban and urban fractions of a catchment (Eq. (1)) and is demonstrated by Kjeldsen et al. (2013) to provide a realistic basis for estimating the percentage runoff. Moreover, comparison with validated impervious data derived using high-resolution aerial photographs, reported by Miller and Grebby (2014) demonstrated that *URBEXT* provides accurate estimates of catchment-level impervious cover (*IMP*):

$$IMP = URBEXT = urban + (0.5 \times suburban), \qquad (1)$$

where *urban* and *suburban* are the proportions of the catchment classified as urban and suburban land use, respectively, and the *suburban* weighting factor (0.5) reflects the mix of pervious and impervious surfaces in such areas (e.g. houses with gardens).

5. Hydrological modelling

5.1. The hydrological model

The Catchment hydrological cycle Assessment Tool (CAT) was developed by Kim et al. (2012a,b) to assess the impacts of urbanization on storm runoff; in particular the impacts of change in impervious cover. Results from previous model applications demonstrate its effectiveness in assessing the hydrologic impact from urbanization (Kim et al., 2012a; Jang et al., 2012) and consequently the model was adopted in this study. A schematic representation of the CAT model structure is shown in Fig. 3.

The CAT model is a physically based semi-distributed hydrological model. It is designed and developed with a 'node-link' type structure that enables routing of runoff from sub-catchments into a full hydrological catchment response. Full details on the function and application of the CAT model are available from Kim et al. (2012a) and the specific settings chosen in the model set-up used in this study include: infiltration calculated by rainfall excess using the Horton method, groundwater movement between sub-catchments based on the Darcy equation to simulated groundwater level, and the Muskingum method is adopted for channel routing.

5.2. Model set-up

The hydrological model is set-up to run on a 15 min timestep and utilizes where possible physical data on catchment characteristics to define model parameters. The aim has been to isolate calibration and sensitivity analyses to model parameters that would change as a result of urbanization. Catchment values for soil, slope and channel parameters were derived from the field observations and geo-spatial data and the resulting calibrated values are listed in Table 2. The effective impervious area (EIA) is defined as the proportion of impervious surfaces hydraulically connected to storm water drainage systems (Han and Burian, 2009). Here the EIA is based upon previous research estimates from the UK that relate EIA to total impervious area (TIA), in this case EIA = 0.7 TIA (Packman, 1980).

Individual storm events used in calibration and validation of modelling were selected according to the peak flow values of the largest observed events at the FBC site (Table 3). As can be seen in Table 3, the magnitude of peak flow for the largest 10 events in the FBC catchment are not all coincident with largest 10 in the other catchments. This was expected as there were no storm events large enough to cause exceptionally high flows or lead to flooding during the monitored period.

In order to determine the impacts of progressive urbanization on storm runoff response, the calibrated hydrological model was used to 'backcast' storm runoff response using historical parameters for each decade and then comparing the hydrological response as predicted using the CAT model. This involved comparing the hydrological response to varying levels of impervious cover during the 1960s to the 2000s and also to both contemporary (2010s) impervious cover with and without the major storm drain system installed to the north and exiting at CWS. The input data for all
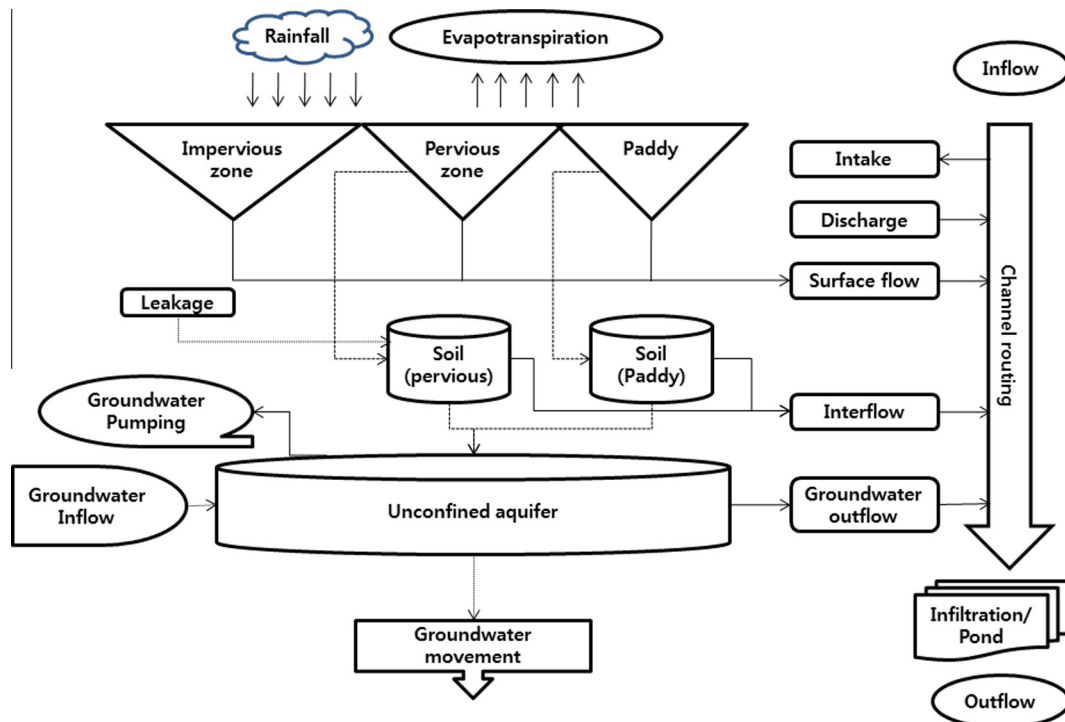

Fig. 3. Schematic diagram of water cycle process in CAT model (Kim et al., 2012a).

Table 2
Key catchment values used as parameters in the hydrological model.

Parameters		Unit	ROD	CWS	FBC	HW
Area	(Area)	km^2	5.51	2.11	3.07	5.79
Slope	(Slope)	–	0.034	0.050	0.045	0.048
Aimp	(Impervious cover)	%	46	51	43	44
Aper	(Total Impervious Cover (TIA))	%	54	49	57	56
EIA	(Effective Impervious Area = 0.7 TIA)	%	32	36	30	31
k	(Routing parameter)	h	3.75	0.5	3.5	3.5
Sdepth	(Soil depth)	m	0.5	0.34	0.42	0.38
θs	Saturated volumetric soil moisture content	m^3/m^3	0.56	0.62	0.58	0.59
θFC	Soil moisture at field capacity(0.05 bar)	m^3/m^3	0.40	0.40	0.37	0.38
θwp	Soil moisture at permeneat wilting point (15 bar)	m^3/m^3	0.15	0.15	0.15	0.15
Ks	(Hydraulic conductivity)	m/s	7×10^{-7}	7×10^{-7}	7×10^{-7}	7×10^{-7}

scenarios are the observed rainfall and potential evapotranspiration for the period May 2011 to October 2012. This forcing data was used to drive the model. No explicit modelling of sustainable urban drainage systems (SUDS) within the study catchments was undertaken as the extent of SUDS was deemed to have very little impact upon the storm runoff response.

5.3. Model calibration

Calibration of all CAT model parameters except impervious cover (Table 2) was undertaken using a trial-and-error approach that involved comparing the simulated results for five selected events from a complete model run with the corresponding observed event hydrograph. A sensitivity analysis was undertaken to identify the parameters that would most significantly affect the simulated storm hydrograph resulting from changes in urban land use. Percentage imperviousness was identified as having most impact on peak flows and the routing parameter k on the timing of peak flows. The routing parameter k was calibrated by observing the time it typically takes for the rising limb of the hydrograph to peak, defined as the 'time-of-rise' (T_R) in hours, for each catchment. With any change in urban cover there is also an associated change in the scale and type of the storm drainage network that will affect the routing velocities, and resulting response time, within the study catchments, as illustrated in various studies (e.g. Burns et al., 2005; Han and Burian, 2009; Mejia and Moglen, 2009). In this study this is replicated using historical values for k determined from the level of urban extent. This proxy approach uses the routing parameter time-to-peak (T_P) of the instantaneous unit hydrograph from the ReFH[2] model (Kjeldsen, 2007) as this incorporates the measure of urban extent URBEXT. The equation for estimating T_P in the ReFH model based on catchment descriptors is given as;

$$T_P = 1.56 \text{PROPWET}^{-1.09} \text{DPLBAR}^{0.60} (1 + URBEXT)^{-3.34} \text{DPSBAR}^{-0.28}$$
(2)

where the variables PROPWET (index of proportion of time that soils are wet), DPLBAR (index describing catchment size and drainage configuration) and DPSBAR (index of catchment steepness) are catchment descriptors taken from the FEH CD-ROM (based on a digital terrain model and observed soil moisture data) and do not vary over time. The relationship in Eq. (2) provides a means for adjusting the Muskingum routing parameter k, based upon the ratio between values of T_P derived from decadal values of URBEXT (Eq. (1)), such that

$$k_t = \frac{(1 + URBEXT_t)^{-3.34}}{(1 + URBEXT_{2010})^{-3.34}} k_{2010}$$
(3)

where t denotes the decade (t = 1960, 1970, . . ., 2010).

---

[2] The ReFH model is an event based rainfall runoff model forming part of the UK Flood Estimation Handbook (FEH).

A robust means of determining variability in EIA for each decade was not determined; however calibration with observed data indicated that setting the EIA to 70% of TIA (Packman, 1980) was a suitable estimate for the study area.

6. Results and discussion

This section is structured to convey the results from: (i) comparing the observed storm runoff response between gauged flow sites, (ii) mapping historical land use change and associated impervious cover, and (iii) backcasting of storm runoff response using historical levels of impervious cover and storm drainage. Results are discussed in relation to differences in land use and drainage type and how progressive urban development has altered the catchments response to storm events.

6.1. Observed storm runoff response

Differences in the observed representative storm hydrograph (mean of the 10 largest events) from each of the three sites demonstrate a highly variable runoff response to storm events. Fig. 4 shows the 10 individual event hydrographs for each site (grey lines) along with the largest event (dotted line) and the mean response (black line) across the 10 events along with a total outflow (HW) for the Haydon Wick brook catchment (combing the 10 highest events at the FBC site with the synchronous events at the CWS site). Across these sites the hydrological metrics of peak flow, time-of-rise (T_R), and characteristic flood duration (θ – defined as $Q/Q_{max} = 0.5$ on the representative mean hydrograph) provide a quantitative means for comparing the resulting representative storm hydrographs.

Within the Haydon Wick catchment there are significant differences in the response between the storm drain system outflow at CWS and the brook at FBC. The FBC hydrograph indicates a representative T_R of 12.25 h and a peak flow of 0.8 m^3 s^{-1} (0.26 m^3 s^{-1} km^{-2}) with a θ of 4 h and the largest event peaking at 1.3 m^3 s^{-1} (0.42 m^3 s^{-1} km^{-2}). While the CWS catchment is slightly smaller (Table 1) and shorter (Fig. 1) the hydrograph observed at CWS exhibit a much flashier response with a T_R of 2 h from near zero baseflow, a reduced θ value of 0.75 h, and a much larger peak flow event of 2.9 m^3 s^{-1} (1.37 m^3 s^{-1} km^{-2}). The more rapid response and higher peak flow in CWS demonstrate the impact of runoff being collected from mixed commercial/residential areas and transported solely via storm drainage networks. When combining the 10 largest synchronous events from FBC and CWS as one outlet (HW) the hydrograph for HW demonstrates the high relative impact that CWS flows have on the overall combined catchment response. The representative storm runoff response from the Rodbourne (ROD) catchment is similar to that of the Haydon Wick brook (FBC), though slightly higher in magnitude (1.0 m^3 s^{-1}

Table 3
Selected storm events with event rainfall, peak flow and event rainfall–runoff ratio.

Event rank (FBC)	Event date-time start	Rain (mm)	FBC Qp (m³ s⁻¹)	FBC Qv (mm)	FBC Percentage runoff ratio (Qv/Rain)	ROD Qp (m³ s⁻¹)	ROD Qv (mm)	ROD Rank	ROD Percentage runoff ratio (Qv/Rain)	CWS Qp (m³ s⁻¹)	CWS Qv (mm)	CWS Rank	CWS Percentage runoff ratio (Qv/Rain)
1	01/05/2012 05:00	14.1	1.29	7.8	0.55	1.46	7.6	1	0.54	2.18	7.6	4	0.54
2	15/08/2012 10:00	21.1	1.03	4.5	0.21	1.15	4.0	2	0.19	2.85	5.5	1	0.26
3	12/07/2012 15:00	16.1	0.96	6.6	0.41	1.10	5.4	3	0.33	1.16	3.3	7	0.21
4	29/08/2012 09:00	21.2	0.76	5.6	0.26	1.02	6.1	4	0.29	2.73	4.3	2	0.20
5	23/09/2012 10:00	37.2	0.72	7.9	0.21	0.87	7.7	9	0.21	1.08	5.0	10	0.13
6	12/06/2011 05:30	18.7	0.65	4.4	0.24	0.93	4.6	8	0.25	0.61	3.2	5	0.17
7	03/01/2012 01:00	9.5	0.64	6.7	0.71	1.00	6.8	6	0.72	1.07	3.7	11	0.39
8	04/10/2012 22:00	13.1	0.59	4.0	0.31	0.68	3.4	10	0.26	0.54	2.3	8	0.17
9	14/12/2011 10:45	8.3	0.34	3.2	0.39	0.68	3.7	5	0.44	0.54	1.5	20	0.18
10	23/06/2012 17:30	19.9	0.53	7.3	0.37	0.72	5.8	14	0.29	0.82	1.8	16	0.09

$(0.18 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2})$) and with a shorter T_R of 11 h and longer flood duration θ of 5.5 h.

The observed hydrographs at both the ROD and FBC locations are characterized by a rapid response to rainfall but also a much more attenuated falling limb of the hydrograph than observed at CWS. This is excepted as both ROD and FBC concurrently receive runoff from sub-surface pathways and storm drainage, while CWS receives runoff solely from impervious areas routed via the storm drain system. The similarities in response to storm runoff between ROD and FBC exists despite the Rodbourne catchment being highly urban and featuring large scale commercial units, while the Haydon Wick is predominantly peri-urban with residential developments. This suggests there is little hydrologic distinction between the urban and peri-urban developments when the impervious cover are similar and no significant hydraulic alteration is present. In contrast, the rapid and flashy response evident in the hydrographs from CWS highlights the impact of a storm drain system with negligible evident contribution from pervious areas or natural drainage. Taken together observations suggest that there is a greater hydrologic distinction between types of drainage system rather than development type.

Evidence from other studies (e.g. Braud et al., 2013; Ogden et al., 2011) suggests the impact of urbanization on runoff generation is less significant for extreme events. No extreme storm events were captured during monitoring period, thus the storm events selected can be considered suitable to assess the impacts of urbanization on storm runoff response.

6.2. Historical change in urban extent and impervious cover

Mapping the decadal change in urban extent across the HW and ROD catchments from historical mapping sources over the period from the 1960s to 2010s has demonstrated that the two catchments have undergone very different patterns of development (Fig. 5). Within the Rodbourne catchment the pattern of development has remained fairly similar, but the intensity has increased through infilling of small pockets of space and redevelopment, turning suburban areas into urban. The pattern in Haydon Wick is a progressive northern expansion of suburban land use and isolated commercial/business development, such that by the 2010s almost the entire catchment area is developed aside from three areas of near-continuous green space. The historical change in urban land use and derived URBEXT and impervious cover (Table 4) demonstrates the quantitative impact of the urban expansion across the study catchments over the period from 1960 to 2010. Within Haydon Wick, impervious cover rose significantly from 11% to 44%, demonstrating a consistent increase each decade, but with the greatest expansion seen in the 1990s and 2000s. Within the Rodbourne catchment impervious cover has risen steadily from 32% to 46%.

With all estimates of historical urban land use and associated impervious cover there is some associated uncertainty, from the digitized topographic mapping to assigning impervious values to land use classes. However, while per-pixel value can vary considerably, Miller and Grebby (2014) demonstrated that derived catchment values performed well against values derived from aerial photography across a number of locations and decades of data ($R^2 = 0.83$–0.96).

6.3. Validation of CAT model

The CAT model was validated using five of the selected ten events to determine how well the model had performed (Table 5). Performance was determined by comparing observed and simulated runoff for each event hydrograph. The criteria selected to measure model performance compared to observed data during
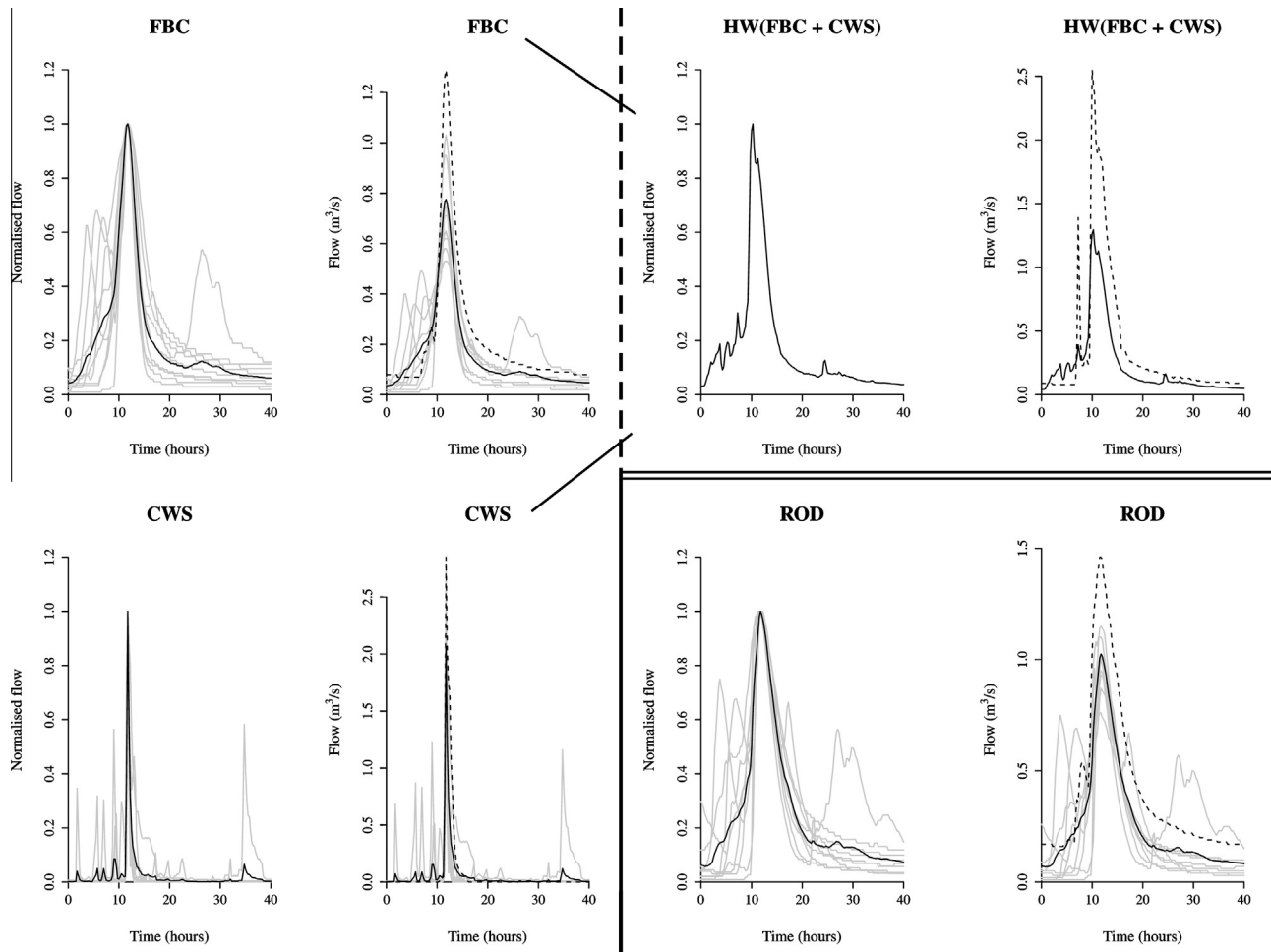
Fig. 4. Normalised and standard event hydrographs at gauged locations for the ten maxima flows recorded during the monitoring period 2011–2012. Grey lines indicate individual event hydrographs; black lines represent the mean hydrograph of the ten events; dotted lines show the largest recorded event. Hydrographs from FBC and CWS are combined into a single accumulated response to illustrate the combined outflow from the altered Haydon Wick (HW) catchment.

calibration and validation include: relative difference error in the peak discharge (ΔQ), absolute difference in timing of peak flows (ΔtQ), along with the Nash–Sutcliffe model efficiency (NSE), defined as;

$$NSE = 1 - \frac{\sum (q_o(t) - q_s(t))^2}{\sum (q_o(t) - \overline{q_o})^2} \tag{4}$$

where $q_s(t)$ denotes simulated discharge (m^3/s) for time t, $q_o(t)$ is observed discharge for time t, and $\overline{q_o}$ is the average discharge of the observed streamflow.

Results from analysis of model performance across both calibration and validation events (Table 5) suggest that across the ten selected events a generally good level of fit was obtained (NSE > 0.7) in reproducing the event hydrographs for the FBC and ROD sites, while the results from CWS site indicate a generally poor level of fit (NSE < 0) but with good reproduction of the two largest events (NSE > 0.8). Peak flows are well replicated at all sites showing average ΔQ values lower than 9% across the ten events. The timing of peak flows was similarly well produced with average ΔtQ values all lower than ±0.28 hours (equivalent to approximately 20 min) across all sites. Modelled hydrograph recessions are less well reproduced, but the comparison between observed and simulated runoff for the two largest events in Fig. 6

demonstrates good reproduction in the timing and magnitude of peak flows.

6.4. Backcasting the storm runoff of progressive development

Mapping of urban extent, *URBEXT*, provided the basis for determining historical values of impervious cover and the Muskinum routing parameter k (Table 4). The decadal k values for Haydon Wick show that the catchment typically took over twice as long to respond to storm rainfall in the 1960s, with an estimated 8 h value progressively reduced to 3.5 h by the 2010s. Within the Rodbourne catchment area the urban extent has changed less over time and this is reflected in only a minor (<1 h) reduction in the routing parameter k over the 50 year period.

The backcasting of the storm runoff using a common rainfall input enables a comparison between the representative hydrograph for each decade. Results are summarised in Table 6 with the representative decadal event hydrographs shown in Fig. 7 (HW and ROD). An increase in impervious cover within the Haydon Wick catchment from 11% in the 1960s to 44% in the 2010s has led to a substantial increase in representative storm peak flows from 0.31 m^3 s^{-1} to 1.65 m^3 s^{-1} (1.34 m^3 s^{-1}), an increase of over 400%, as well as a reduction in the flood duration θ of 7.75 hours T_R of 3.75 h (51%). A comparison between the contemporary storm runoff response for Haydon Wick with the partitioned storm drainage
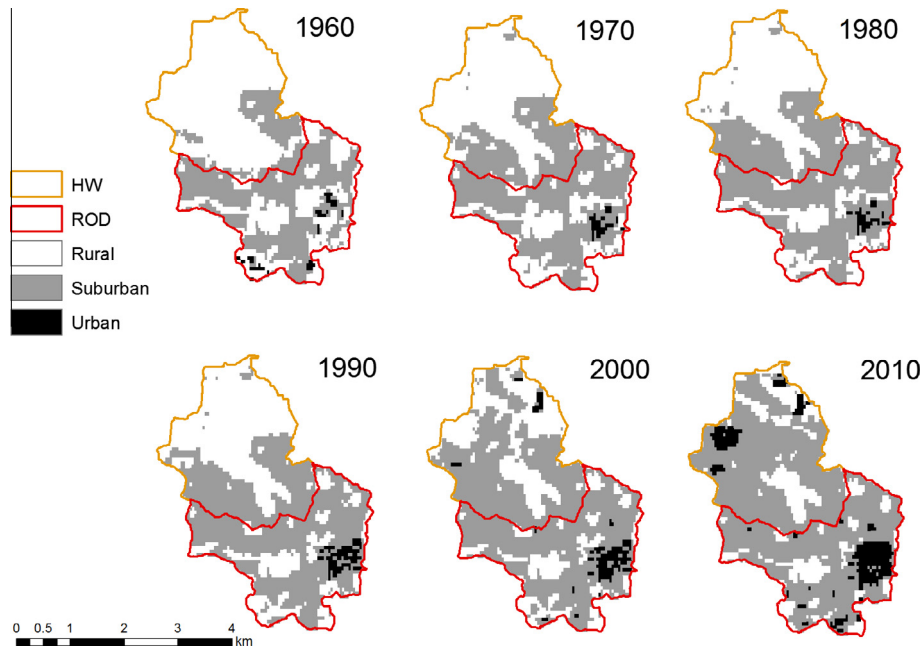
Fig. 5. Change in urban land use (1960–2010) across study catchments.

Table 4
Decadal values of urban extent *URBEXT* (also impervious cover *IMP*) and derived values for time-to-peak (T_P) routing parameter k derived using Eq. (3).

Catchment	Index	Year						
		1960	1970	1980	1990	2000	2010	2010a
CWS	*URBEXT(IMP)*							0.47
	k (h)							0.5
Haydon Wick	*URBEXT(IMP)*	0.11	0.18	0.20	0.22	0.32	0.44	0.42
	T_P	2.53	2.03	1.95	1.85	1.42	1.06	1.11
	Ratio	2.39	1.92	1.84	1.75	1.34		
	k (h)	8.00	6.50	6.00	5.75	4.50	3.50	3.50
Rodbourne	*URBEXT(IMP)*	0.32	0.34	0.36	0.39	0.41	0.46	
	T_P	1.4	1.3	1.3	1.2	1.1	1.01	
	Ratio	1.4	1.3	1.3	1.2	1.1		
	k (h)	4.50	4.50	4.50	4.00	4.00	3.75	

Table 5
Summary of model performance at each site across the 10 selected calibration and validation events: NSE – Nash–Sutcliffe model efficiency, ΔQ – relative difference error in the peak discharge, ΔtQ – absolute difference in timing of peak flows.

Flood event	Calibration/ validation	CWS					FBC					ROD				
		Q_o (m³/s)	Q_s (m³/s)	NSE	ΔQ (%)	ΔtQ (h)	Q_o (m³/s)	Q_s (m³/s)	NSE	ΔQ (%)	ΔtQ (h)	Q_o (m³/s)	Q_s (m³/s)	NSE	ΔQ (%)	ΔtQ (h)
1	C	2.18	2.21	0.88	1.7	0.25	1.29	0.99	0.87	−23.3	0.50	1.46	1.50	0.97	2.7	0.25
2	V	2.85	2.55	0.88	−10.4	0.25	1.03	1.03	0.92	0.4	−0.25	1.15	1.44	0.80	25.5	0.50
3	V	1.16	1.24	−0.11	7.0	−0.25	0.96	0.79	0.86	−17.7	−0.50	1.10	1.10	0.91	−0.4	0.25
4	V	2.73	2.56	0.70	−6.1	0.25	0.76	0.97	0.65	27.8	−0.50	1.02	1.33	0.68	29.9	0.00
5	V	1.08	1.01	−0.77	−6.6	0.00	0.72	0.75	0.77	4.7	0.25	0.87	1.06	0.69	21.5	0.75
6	C	0.61	0.89	−0.27	46.2	0.00	0.65	0.64	0.95	−1.6	0.00	0.93	0.89	0.87	−4.5	1.00
7	C	1.07	0.99	−0.04	−8.2	0.00	0.64	0.57	0.88	−11.0	−0.25	1.00	0.85	0.60	−14.9	0.50
8	V	0.54	0.73	−2.00	35.6	1.75	0.59	0.69	0.91	16.9	−0.50	0.68	0.89	0.68	31.7	−1.50
9	C	0.54	0.76	−1.45	41.0	0.00	0.34	0.32	0.71	−5.4	0.75	0.68	0.44	0.31	−35.2	2.00
10	C	0.82	0.72	−2.31	−12.1	0.25	0.53	0.55	0.82	3.4	−1.25	0.72	0.75	0.85	4.3	−1.00
x				−0.45	8.82	0.25			0.83	−0.58	−0.18			0.74	6.07	0.28

system (2010a) and a 'conceptual' scenario (2010) without this system and that drains via the FBC site as was the case pre-2000 demonstrates the implementation of the storm drainage system acts to significantly increase peak flows and reduce both θ and T_R. The changes within Haydon Wick contrast with the Rodbourne catchment where an increase in impervious area from 32% to 46%

results in an absolute increase in peak flow from 0.76 m³ s⁻¹ to 1.12 m³ s⁻¹ (0.36 m³ s⁻¹ (47%)) and reduction in flood duration θ of 1 h with little change in the timing of flows.

Results show that a similar rise (14%) in impervious cover in both Haydon Wick (18–32% – 1970–2000) and Rodbourne (32–46% – 1960–2010) resulted in different scale impacts on the
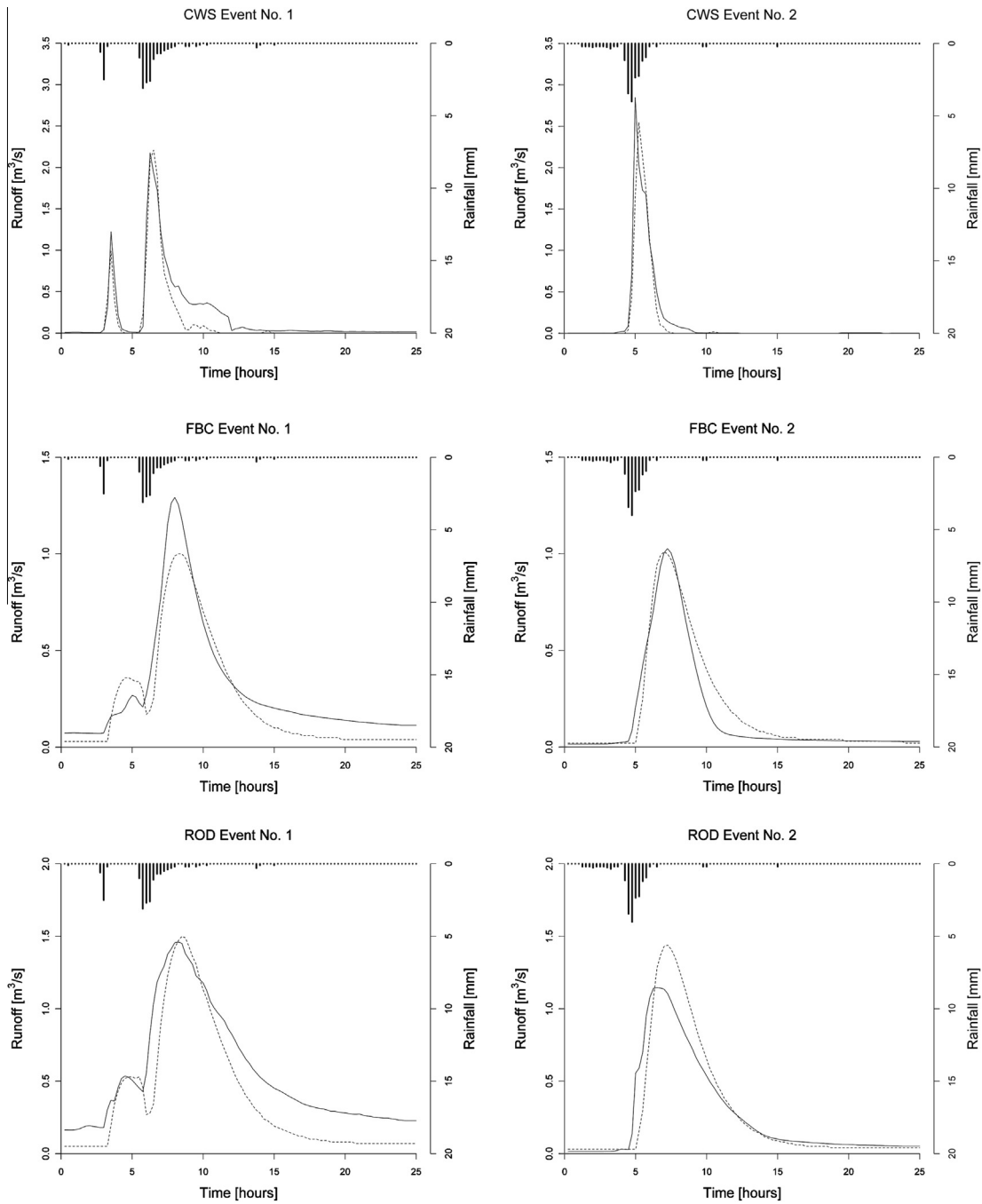
Fig. 6. Selected calibration (left) and validation (right) events for each gauged site (flow and rainfall are measured at a 15 min timestep).

Table 6
Results from modelling the mean 'representative' storm runoff response for each decade across ten selected events: *IMP* – total impervious area, Q_P – peak flow, θ – flood duration, T_R – time of rise.

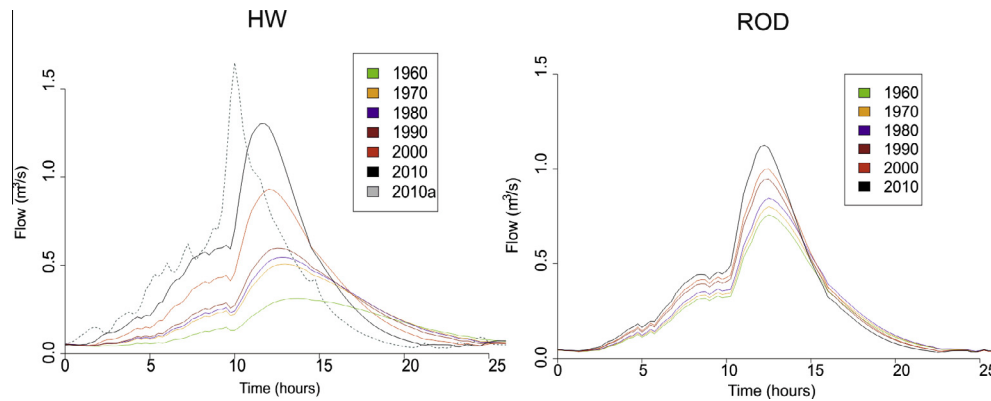| Decade	ROD				HW			
	IMP (%)	Q_P (m^3 s^{-1})	Θ (h)	T_R (h)	*IMP* (%)	Q_P (m^3 s^{-1})	Θ (h)	T_R (h)
1960	32	0.76	5.5	12.75	11	0.31	10.5	14
1970	34	0.80	5.5	12.75	18	0.51	8.25	13.25
1980	36	0.85	5.5	12.75	20	0.55	8	13
1990	39	0.95	5	12.75	22	0.60	7.25	12.75
2000	41	1.0	5	12.75	32	0.93	5.5	12.25
2010	46	1.12	4.5	12.5	44	1.65	2.75	10.25
2010a	–				44	1.30	4.5	12

Fig. 7. Representative storm hydrographs for each decade (derived as the mean hydrograph of ten selected storm events for each decade) from modelling of the Haydon Wick (HW) and Rodbourne (ROD) catchment. (2010a refers to the current catchment arrangement with a storm drainage system receiving storm runoff from northern areas while 2010 is a conceptual scenario for the same level of impervious cover but without this system).

storm runoff response. The increase in absolute and relative peak flow increase was much greater for Haydon Wick ($0.42 \, m^3 \, s^{-1}$ (82%)) compared to the more developed Rodbourne catchment ($0.36 \, m^3 \, s^{-1}$ (47%)). There was also a much greater increase in flood duration θ in Haydon Wick of 3 h, compared to 1 h in Rodbourne. This highlights that increases in impervious cover for the more rural catchment have a much greater impact on peak flows and the duration of floods than for an existing urban area.

7. Conclusions

This study uses a combination of hydro-meteorological observations and historical mapping of land use change as inputs to a hydrological model, thereby enabling an assessment of the impacts on storm runoff response of developing a rural to peri-urban area and how this compares with concurrent changes in a more mature urban area. Taken together the monitoring and modelling provide a number of important conclusions. First, that the combination of a high proportion of impervious cover and routing of all storm runoff via a storm drainage network can lead to a much flashier response and higher peak flows than would be attributed by increases in impervious cover or change in land use alone. Second, that increases in impervious cover for rural catchments can have a much greater impact on peak flows and the duration of floods than for an existing urban area. Lastly, that little distinction in hydrological response exists between urban and peri-urban developments of similar impervious cover when no significant hydraulic alteration is present.

The results from this study provide further evidence that: (i) any relationship between Effective Impervious Area (EIA) and Total Impervious Area (TIA) will vary considerably depending on urban design and local factors (Jacobson, 2011; Roy and Shuster, 2009), and (ii) that storm drainage and flood attenuation features are important components to consider when attributing storm event response (Meierdiercks et al., 2010). Simplified classifications of urban land use and imperviousness alone cannot account for hydraulic alterations that significantly affect the hydrological response of a catchment to storm events. This demonstrates the requirement for more detailed urban land use typologies, beyond impervious area or simplified land use classes that better represent some inherent hydrological metrics of form and function that could define representative hydrological pathways, both above and below ground. Such information is becoming more important when considering future developments that are increasingly required to employ mitigation measures such as SUDS and the trend towards infilling of urban areas (Perry and Nawaz, 2008). Similarly, there is an accompanying need to consider at what scale

such alterations affect a change in the storm runoff response of a catchment and at what scale detailed information on land use improves the predictive ability of hydrological modelling. Future work will seek to develop more hydrologically representative land use information and assess the potential for attribution with more refined scale hydro-meteorological observations across a number of scales and locations.

Flooding still exists within the Haydon Wick catchment and flood alleviation works comprising raising the elevation of the stream bank to contain high flows were identified as the most suitable option (EA, 2010) and have been implemented during 2013. The choice of traditional flood defence measures rather than SUDS indicates the challenge faced when attempting to retrofit flood mitigation measures in such a highly developed area where flood protection is urgently required.

References

Alexander, E.B., 1980. Bulk densities of California soils in relation to other soil properties. Soil Sci. Soc. Am. J. 44, 689–692.

Braud, I., Breil, P., Thollet, F., Lagouy, M., Branger, F., Jacqueminet, C., Kermadi, S., Michel, K., 2013a. Evidence of the impact of urbanization on the hydrological regime of a medium-sized periurban catchment in France. J. Hydrol. 485, 5–23.

Braud, I., Fletcher, T.D., Andrieu, H., 2013b. Hydrology of peri-urban catchments: processes and modeling. J. Hydrol. 485, 1–4.

Burges, S.J., Wigmosta, M.S., Meena, J.M., 1998. Hydrological effects of land use change in a zero-order catchment. J. Hydrol. Eng. 3 (2), 86–97.

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., Kendall, C., 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. J. Hydrol. 311 (1), 266–281.

Canters, F., Batelaan, O., de Voorde, T.V., Chormański, J., Verbeiren, B., 2011. Use of impervious surface data obtained from remote sensing in distributed hydrological modeling of urban areas. In: Yang, X. (Ed.), Urban Remote Sensing: Monitoring, Synthesis and Modeling in the Urban Environment. John Wiley & Sons, Chichester, UK, pp. 255–273.

Chormanski, J., Van de Voorde, T., De Roeck, T., Batelaan, O., Canters, F., 2008. Improving distributed runoff prediction in urbanized catchments with remote sensing based estimates of impervious surface cover. Sensors 8, 910–932.

Dams, J., Batelaan, O., Nossent, J., Chormanski, J., 2009. Improving hydrological model parameterisation in urbanised catchments: Remote sensing derived impervious surface maps. In: Feyen, J., Shannon, K., Neville, M. (Eds.), Water and Urban Development Paradigms: Towards and Integration of Engineering Design and Management Approaches. CRC Press, Taylor Francis Group, Boa ration, Florida, USA.

Department for Communities and Local Government. 2012. National Planning Policy Framework. <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6077/2116950.pdf>.

Environment Agency, 2008. Swindon Floods Review: July 2007. An investigation into the causes and flood risk management options. February 2008.

Environment Agency, 2010. Haydon Wick Brook Flood Allieviation Scheme: Hydrology Report. Royal Haskoning.

Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters; a state of the art review. Adv. Water Resour. 51, 261–279.

Fuller, R.M., Smith, G.M., Sanderson, J.M., Hill, R.A., Thomson, A.G., 2002. The UK Land Cover Map 2000: construction of a parcel-based vector map from satellite images. Cartographic J. 39, 15–25.

Gerard, F. et al., 2010. Land cover change in Europe between 1950 and 2000 determined employing aerial photography. Prog. Phys. Geogr. 34 (2), 183–205.

Hall, D.G.M., Reeve, M.J., Thomasson, A.J., Wright, V.F., 1977. Water retention, porosity and density of field soils (Technical Monograph No. 9), Rothamsted Experimental Station, Harpenden, UK.

Han, W.S., Burian, S.J., 2009. Determining effective impervious area for urban hydrologic modeling. J. Hydrol. Eng. 14, 111–120.

Hawley, R.J., Bledsoe, B.P., 2011. How do flow peaks and durations change in suburbanizing semi-arid watersheds? A southern California case study. J. Hydrol. 405, 69–82.

Hollis, G.E., 1975. The effect of urbanization on floods of different recurrence interval. Water Resour. Res. 11 (3), 431–435.

Howard Humphreys & Partners, 1986. River Ray Catchment Study. Consultancy Report for Thames Water, UK. pp 189.

Huang, H.J., Cheng, S.J., Wen, J.C., Lee, J.H., 2008. Effect of growing watershed imperviousness on hydrograph parameters and peak discharge. Hydrol. Process. 22, 2075–2085.

Institute of Hydrology, 1999. Flood Estimation Handbook, vol. 5. Centre for Ecology and Hydrology, Wallingford, UK.

Jacobson, C.R., 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. J. Environ. Manage. 92, 1438–1448.

Jang, C.H., Kim, H., Kim, J.T., 2012. Prediction of Reservoir Water Level using CAT. J. Korea Soc. Agric. Eng. 54 (1), 27–38.

Kim, H., Jang, C.H., Noh, S.J., 2012a. Development and application of the catchment hydrologic cycle assessment tool considering urbanization (I) model development. J. Korea Water Res. Assoc. 45 (2), 203–215.

Kim, H., Jang, C.H., Noh, S.J., 2012b. Catchment Hydrologic Cycle Assessment Tool User Guide, Korea Institute of Construction Technology. <http://watercycle.re.kr> (accessed 30.01.13).

Kjeldsen, T.R., 2007. The Revitalised FSR/FEH Rainfall-Runoff Method. NERC/Centre for Ecology & Hydrology, Wallingford.

Kjeldsen, T.R., Miller, J.D., Packman, J., 2013. Modelling design flood hydrographs in catchments with mixed urban and rural land cover. Hydrol. Res. 44 (6), 1040–1057.

Marsh, T.J., Parry, S., Kendon, M.C., Hannaford, J., 2013. The 2010-12 Drought and Subsequent Extensive Flooding. Centre for Ecology & Hydrology, 54 p.

Mayr, T., Jarvis, N.J., 1999. Pedotransfer functions to estimate soil water retention parameters for a modified Brooks–Corey type model. Geoderma 91, 1–9.

Meierdiercks, K.L., Smith, J.A., Baeck, M.L., Miller, A.J., 2010. Analyses of urban drainage network structure and its impact on hydrologic response1. JAWRA J. Am. Water Res. Assoc. 46 (5), 932–943.

Mejia, A.I., Moglen, G.E., 2009. Spatial patterns of urban development from optimization of flood peaks and imperviousness-based measures. J. Hydrol. Eng. 14, 416–424.

Miller, J.D., Grebby, S., 2014. Utilizing aerial photography with topographical maps for long-term temporal mapping of imperviousness. Int. J. Appl. Earth Obs. Geoinform. 30, 9–20.

Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R., Simpson, I.C., 2011. Final Report for LCM2007 – The New UK Land Cover Map. CS Technical, Report No 11/07.

Ogden, F.L., Pradhan, N.R., Downer, C.W., Zahner, J.A., 2011. Relative importance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment. Water Resour. Res. 47, W12503. http://dx.doi.org/10.1029/2011WR010550.

Office for National Statistics, 2012. National Population Projections, 2012-based Statistical Bulletin. <http://www.ons.gov.uk/ons/dcp171778_334975.pdf>.

Packman, J., 1980. The effects of urbanisation on flood magnitude and frequency. Institute of Hydrology Report No 63. Wallingford, Oxfordshire.

Perrin, J.L., Bouvier, C., Janeau, J.L., Menez, G., Cruz, F., 2001. Rainfall/runoff processes in a small peri-urban catchment in the Andes mountains. The Rumihurcu Quebrada, Quito (Ecuador). Hydrol. Process. 15, 843–854.

Perry, T., Nawaz, R., 2008. An investigation into the extent and impacts of hard surfacing of domestic gardens in an area of Leeds, United Kingdom. Landscape Urban Plann. 86, 1–13.

Piorr, A., Ravetz, J., Tosics, I. (Eds.), 2011. Peri-Urbanisation in Europe: Towards European Policies to Sustain Urban-Rural Futures. <http://www.plurel.net/images/Peri_Urbanisation_in_Europe_printversion.pdf>.

Roy, A.H., Shuster, W.D., 2009. Assessing impervious surface connectivity and applications for watershed management. J. Am. Water Resour. Assoc. 45 (1), 198–209.

Scholz, M., Yazdi, S.K., 2009. Treatment of road runoff by a combined storm water treatment, detention and infiltration system. Water Air Soil Pollut. 198 (1–4), 55–64.

Simmons, D.L., Reynolds, R.J., 1982. Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. J. Am. Water Resour. Assoc. 18, 797–805.

Tavares, A.O., Pato, R.L., Magalhães, M.C., 2012. Spatial and temporal land use change and occupation over the last half century in a peri-urban area. Appl. Geogr. 34, 432–444.

United Nations, 2008. United Nations expert group meeting on Population Distribution, Urbanization, Internal Migration and Development. United Nations Population Division. <http://sustainabledevelopment.un.org/content/documents/2529P01_UNPopDiv.pdf>.

Ward, H.C., Evans, J.G., Grimmond, C.S.B., 2013. Multi-season eddy covariance observations of energy, water and carbon fluxes over a suburban area in Swindon, UK. Atmos. Chem. Phys. Discuss. 12, 29147–29201.

Wostern, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185.