Modelling design flood hydrographs in catchments with mixed urban and rural land cover

T. R. Kjeldsen, J. D. Miller and J. C. Packman

ABSTRACT

The effect of urban land cover on catchment flood response is evaluated using a lumped rainfall–runoff model to analyse flood events from selected UK catchments with mixed urban and rural land use. The present study proposes and evaluates a series of three extensions to an existing model to enable a better representation of urban effects, namely: an increase in runoff volume, reduced response time and a decrease in baseflow (resulting from decreased infiltration). Based on observed flood events from seven catchments, cross-validation methods are used to compare the predictive ability of the model variants with that of the original unmodified model. The results show that inclusion of urban effects increases the predictive ability of the model across catchments, despite large between-event variability of model performance. More detailed investigations into the relationship between model performance and individual event characteristics (antecedent soil moisture, rainfall duration, depth and intensity) did not reveal systematic inabilities of the model to reproduce certain types of events. Finally, it is demonstrated that the new extended model has the ability to simulate urban effects in accordance with the expected changes in storm runoff patterns.

Key words | design flood estimation, floods, rainfall–runoff modelling, urbanisation

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INTRODUCTION

Event-based rainfall–runoff modelling plays an important role in practical flood hydrology for design and management of hydraulic infrastructure and broader flood management around the world. Examples of event-based flood models include the widely used Soil Conservation Service (SCS) method (e.g. Chow *et al.* 1988), the Australian rainfall–runoff model (Pilgrim 1987), the British Flood Studies Report (FSR) model published by the Natural Environment Research Council (NERC 1975) and the more recently developed Revitalised Flood Hydrograph (ReFH) model documented by Kjeldsen *et al.* (2006). The purpose of this type of storm runoff model is to provide a flow hydrograph at the catchment outlet, which then forms the input to a more detailed hydraulic model representing the local geometry as required for engineering design studies (e.g. Shepherd *et al.* 2011; Brandimarte & Di Baldassarre 2012; Faulkner *et al.* 2012).

The effects of urbanisation on catchment storm runoff characteristics have long been recognised, but how best to incorporate them into hydrological catchment models remains an open research question (Borah 2011). This is especially true for medium- to larger-scale catchments with a complex mixture of rural and urban land cover. It is generally accepted that an increase in urban extent or impervious area should result in decreased infiltration capacity and surface storage, thereby increasing runoff volumes. At the same time, the replacement of natural drainage paths with more efficient man-made drainage structures will reduce catchment response times. The combination of these two effects will increase peak flow, as reported by numerous researchers studying observational evidence (e.g. Leopold 1968; Hollis 1975; Sauer *et al.* 1983; Sheng & Wilson 2009). However, the magnitude of the effects can vary considerably between catchments. For

example, Sauer *et al.* (1983) listed a number of local factors which might act to curtail peak flow values in urban areas, such as the existence of detention ponds and temporary storage caused by hydraulic infrastructure (bridges, culverts, embankments, etc). In a study of annual maximum peak-flow values from 200 catchments located in the UK and with more than 5% urban land cover, Kjeldsen (2010) reported that in certain catchments estimates of the flood characteristics are less than what would have been expected had the catchment been in a completely rural state. This again highlights the complex nature of catchments with mixed land-use classes. The effects of urban development are also likely to vary from storm to storm, being reportedly greater for smaller storms (e.g. Packman 1980; Sauer *et al.* 1983).

In a review of urban effects on catchment flood hydrology, Packman (1980) listed four barriers to the development of generic rainfall–runoff models for assessing the effects of urbanisation: (1) an increase in the complexity of the hydrological cycle; (2) defining a suitable parameterisation of the urban effects; (3) a general lack of reliable hydrometric data from urban catchments; and (4) difficulties in generalising the site-specific results for more general use in ungauged catchments. While some work has been undertaken in the UK analysing runoff data from urban catchments on a very small scale, e.g. individual roofs, car parks and roads (e.g. Hollis & Ovenden 1988; Ragab *et al.* 2003), little or no recent effort has been reported on modelling effects of urban land cover at a catchment-wide scale, especially concerning event-based models used for design flood estimation. A study by Beskeen *et al.* (2011) provides an illustrative case study, highlighting many of the practical issues facing hydrologists attempting flood modelling in heavily urbanised catchments.

The ReFH model is a lumped conceptual rainfall–runoff model with a unit-hydrograph-based routing component that has become the *de facto* standard for design flood hydrograph estimation in the United Kingdom (Calver *et al.* 2009; Environment Agency 2009; Faulkner & Barber 2009; Beskeen *et al.* 2011; Faulkner *et al.* 2011). While the ReFH model has so far been used mainly on UK catchments and data, it is a generic rainfall–runoff model built on well-known hydrological modelling principles. Results presented here will therefore also be of interest to hydrologists outside the United Kingdom. For example, the model is also being trialled for use in South Korea (Lee & Joo 2012). Despite its widespread use, it is recognised that the model in its present formulation might not be suitable for use on catchments with extensive urban land cover (Kjeldsen *et al.* 2006; Environment Agency 2009).

In this study, the ReFH model will be extended to incorporate impacts of urban land cover into the mathematical representation of the hydrological processes controlling storm runoff. In particular, the effects on runoff production, catchment response time and baseflow time will be considered. Based on observed flood events from seven urban catchments, a leave-one-out (or cross-validation) technique will be used to compare the gain in predictive ability of different urban model variants when compared to the initial model without urban considerations.

THE REVITALISED FLOOD HYDROGRAPH MODEL

The ReFH model was developed as an event-based rainfall–runoff model for use in design flood estimation tasks within the UK. It has mostly replaced the model published in the NERC (1975) FSR, and restated in the Flood Estimation Handbook (FEH) (Houghton-Carr 1999). Like the FSR model (and other similar event-based models), the ReFH model consists of three components: (1) a loss model where the input hyetograph is transformed into the excess rainfall hyetograph, conditional on the initial wetness of the catchment; (2) a unit-hydrograph-based model for routing excess rainfall to the catchment outlet; and (3) a baseflow model representing the flow in the river before the onset of a storm and the slow flow response.

ReFH was specifically developed as a parameter-sparse model to allow spatial generalisation and thus enable use of the method in ungauged catchments through integration with national datasets of catchment descriptors available for all UK catchments larger than $0.5 \, \text{km}^2$ (CEH 2009). Comprehensive documentation of the background and datasets used for model development can be found in Kjeldsen *et al.* (2006); only a summary of the model components is provided here.

Loss model

The loss model converts the total rainfall hyetograph into excess runoff based on the probability distributed model (PDM; Moore 2007) used widely in the UK. This model treats soil moisture storage over the catchment as a distribution of elemental stores of different depth. In ReFH, a uniform distribution of elemental stores ranging in depth from zero to C_{max} is chosen. As stores fill under rainfall, direct runoff (excess rainfall) begins to occur. Considering an initial condition where each store is already full or contains an equal depth of water C_{t-1}, simple geometry determines that for a rainfall depth of P_t in time interval $[t-1, t]$, the proportion of rainfall converted into direct runoff PR_t and the water depth condition of the next time-step C_t are given by:

$$PR_t = \frac{C_{t-1}}{C_{max}} + \frac{P_t}{2C_{max}}, \quad C_t = C_{t-1} + P_t \tag{1}$$

where C_{max} is the only model parameter, representing twice the mean soil storage capacity of the catchment. The loss model in Equation (1) used to calculate direct runoff is evaluated sequentially during a storm event and all rainfall becomes excess rainfall once the catchment becomes fully saturated (i.e. $PR_t = 1$ for $C_{t-1} = C_{max}$). To initiate the calculations, the loss model requires an estimate of the initial soil moisture content C_{ini} at the onset ($t = 0$) of each event. Estimates of C_{ini} for each event are obtained by running a separate lumped conceptual daily soil moisture model starting in the midwinter that precedes the event by between 1 and 2 years, assuming that the soil is at field capacity at the start of that period (Kjeldsen *et al.* 2006). This model is also based on the PDM but includes evapotranspiration and drainage from the soil column.

Routing model

Analysing flood events from 101 catchments located across the UK, Kjeldsen *et al.* (2006) developed an instantaneous unit hydrograph (IUH) in the form of a 'kinked triangle' for routing effective runoff to the catchment outlet within the ReFH model, as shown in Figure 1. The shape of the IUH is determined by three parameters:
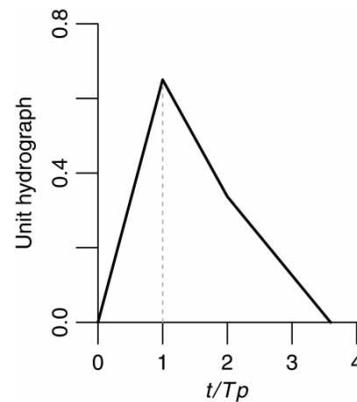

Figure 1 │ Instantaneous unit hydrograph (IUH) of ReFH model.

a scaling parameter (time-to-peak, T_p) and two dimensionless parameters U_p and k_u, controlling the height (peak) and degree of kink of the IUH (the subscripts p and u refer to 'peak' and 'unit hydrograph', respectively). A more detailed description of the IUH is provided in the appendix (available online at http://www.iwaponline.com/nh/044/158.pdf).

The IUH is converted into a unit hydrograph for the required time-step using a standard S-curve technique, and the routed direct runoff q_t is obtained through the discrete-time form of the convolution equation as

$$q_t = \sum_{i=1}^{t} (PR_i P_i) u_{t-i+1} \tag{2}$$

where u_t is the ordinate of the unit hydrograph. The two dimensionless parameters, U_p and k_u, are fixed at default values recommended by Kjeldsen *et al.* (2006).

Baseflow model

The baseflow component of the flood hydrograph is modelled using a linear reservoir where outflow (baseflow z_t) is related to storage in a baseflow reservoir S_t as

$$S_t = BLz_t \tag{3}$$

where the storage constant BL represents the baseflow lag. Next, the mass-balance for the baseflow reservoir considering only recharge into the reservoir and outflow

(baseflow) is given as

$$\frac{\mathrm{d}S}{\mathrm{d}t} = r_t - z_t \tag{4}$$

where recharge r_t is defined under the assumption that only the saturated areas that contribute to direct runoff also contribute to recharge. In the model, this can be expressed by relating the recharge directly to the routed direct runoff as

$$r_t = \mathrm{BR}q_t \tag{5}$$

where BR is a model parameter controlling recharge into the baseflow reservoir. Linking recharge to routed direct runoff gives a significant advantage in that the two baseflow parameters can be determined directly from event recessions rather than as part of the multidimensional optimisation scheme used for the other model parameters. This reduces the complexity of model calibration and the consequent uncertainty in calibrated parameter values.

Combining Equations (3), (4) and (5) and assuming that the routed direct runoff changes linearly over a time-step, the baseflow can be approximated as a recurrence formula linking baseflow to direct runoff and previous baseflow values as

$$z_t = k_1 q_{t-1} + k_2 q_t + k_3 z_{t-1} \quad t = 1, 2, \ldots \tag{6}$$

where the coefficients k_1, k_2 and k_3 are constants and functions of the two baseflow parameters BL and BR (Kjeldsen *et al.* 2006). The model needs a first flow value (initial baseflow) z_0, which is taken as the last available observed flow value before the hydrograph starts to rise when simulating observed flood events. It should be noted that baseflow is generally a fairly small component of any flood peak, but is an increasingly significant component of the event recession. Note also that ReFH is calibrated as a complete model, so the fitted direct runoff parameters will compensate to some extent for any lack of fit to baseflow.

Total flow

Finally, the total flow Q_t is obtained by summing routed direct runoff with baseflow.

INCORPORATING URBANISATION INTO ReFH

Now that the three basic model components have been outlined, the issue of how to incorporate the effects of urbanisation on hydrological processes in the model will be presented. As discussed in the Introduction, the effect of urbanisation is generally considered to be an increase in direct storm runoff volume (mainly through a decrease in infiltration), and a decrease in catchment response times. The following section describes how these effects were translated into conceptual model components for each of the three ReFH model components: loss model, baseflow model and routing model. However, before doing so it is first necessary to discuss the national dataset of land cover (including urbanisation) available for the UK and the hydrological interpretation of these data, especially the link between urban land cover and imperviousness.

Mapping urban extent from land-cover maps

There is no readily available data on the extent of impervious land cover for UK catchments, but the extent of general urban area can be obtained from various sources. When the FSR design flood procedures were developed for use in the UK in the early 1970s (NERC 1975), the spatial extent of urbanisation was extracted manually from 1:50,000 paper maps and quantified as the fraction of catchment areas classified as urban development (URBAN$_{50k}$) including city centres, industrial areas and suburban residential areas. Subsequently, the FEH moved from manually to digitally derived catchment descriptors, and a 50 m grid of UK land cover, obtained from satellite imagery from the year 2000, was used to develop a more refined composite index of urban extent (URBEXT$_{2000}$) for all catchments larger than 0.5 km^2 (Bayliss *et al.* 2006). The URBEXT$_{2000}$ index is derived from three land-cover classes, urban and suburban land cover and inland bare ground (e.g. gravel car parks, railway sidings and derelict industrial land) when found in an urban context. For suburban, half of each pixel is assumed to be urban and the other half non-urban, e.g. gardens and parks. For inland bare ground, Bayliss *et al.* (2006) suggested that 80% of each pixel should be considered as urban.

Bayliss *et al.* (2006) reported an empirical relationship between $URBAN_{50k}$ and $URBEXT_{2000}$ of $URBAN_{50k} = 1.567\, URBEXT_{2000}$. It should be noted that this equation cannot apply to 'extremely heavily urbanised' catchments ($URBEXT_{2000} \geq 0.6$), therefore limiting the extensions discussed below. This relationship will be used in the following sections to derive the hydrological response from the fractions of the catchment considered urban and rural (or non-urban).

Loss model

An intuitive extension of a percentage runoff type loss model was suggested for use in the UK with the FSR rainfall–runoff model by Packman (1980), inspired by earlier work from the USA by Snyder (1958) and Carter (1961), where the percentage runoff is considered as a weighted sum of contributions from the rural and urban parts of the catchment. This model formulation was found to improve the performance of the ReFH model when applied on an urban catchment (Kjeldsen 2009). However, a modified model formulation is adopted here to ensure logical consistency when later considering the routing and baseflow models.

In this study, the model will be formulated considering the two broad land-cover classes: urban (including urban, suburban and inland bare ground) and rural (or non-urban). The percentage runoff is estimated separately for each of the two land-cover classes, and the total runoff derived as a weighted average of the contribution from each class according to spatial extent, i.e.

$$PR = (1 - URBAN_{50k})PR^{(rural)} + URBAN_{50k}PR^{(urban)} \qquad (7)$$

where $PR^{(rural)}$ is the percentage runoff from the rural part of the catchment estimated using the original loss model in Equation (1) and $PR^{(urban)}$ is the percentage runoff from the urban area. To estimate percentage runoff from the urban area, it is assumed that 30% of an urban area is made up of impervious area (Packman 1980) and that $PR^{(urban)}$ consists of contributions from both impervious and pervious areas; the latter is assumed to behave similarly to rural areas as described in Equation (1). The percentage runoff from an urban area is therefore defined:

$$PR^{(urban)} = 0.3PR^{(imp)} + 0.7PR^{(rural)} \qquad (8)$$

where the percentage runoff from an impervious area $PR^{(imp)}$ is taken as 70% (Packman 1980). It should be noted that the assumptions of 30% imperviousness and 70% runoff given in Equation (8) were validated using observed runoff data (Packman 1980), but were left explicit in the equation so that users could adopt different values for special cases (e.g. in dense city centre catchments). Combining Equations (7) and (8) with the Bayliss *et al.* (2006) relationship between $URBAN_{50k}$ and $URBEXT_{2000}$, subject to the limit of $URBEXT_{2000} < 0.6$ discussed above, the percentage runoff model in Equation (7) can be written:

$$
\begin{aligned}
PR &= (1 - 1.576\, URBEXT_{2000})PR^{(rural)} \\
&\quad + 1.576\, URBEXT_{2000}(0.3PR^{(imp)} + 0.7PR^{(rural)}) \\
&= (1 - 0.4701\, URBEXT_{2000})PR^{(rural)} \\
&\quad + 0.4701\, URBEXT_{2000}PR^{(imp)} \qquad (9)
\end{aligned}
$$

The split between rural and urban areas, in contrast to the split between pervious and impervious areas used by Packman (1980) and Kjeldsen (2009), was introduced as it was considered more realistic to define a separate routing model for the entire urban area rather than for the impervious areas alone. Moreover, no data are available from a wholly impervious catchment to permit calibration near the model limits. The urban routing model is discussed in the following section.

Routing model

Previous studies in the UK (e.g. NERC 1975; Kjeldsen *et al.* 2006) of the variation in response time (as measured by the unit hydrograph time-to-peak parameter, T_p) between catchments have found a strong urbanisation influence. In contrast, attribution of changes in response time between events to temporal changes in land cover within catchments has not previously been reported in the UK. In this study, an attempt to capture the anticipated reduction in response time has been made by introducing separate unit hydrographs for routing the excess rainfall generated from the rural and urban parts of the catchment as calculated by the percentage runoff calculations in Equation (9) above. The time-to-peak parameter value for the urban area is expressed as a ratio of the (larger) T_p for the rural area,

but the basic dimensionless shape of the IUH has been kept the same as for the rural area (Figure 1), both for simplicity and under the assumption that reductions in response time will affect both time to peak and time base of the unit hydrograph equally.

Baseflow model

In an urban catchment, the existence of impervious areas will lead to an increase in direct runoff as described in Equation (9). Because of the direct link between routed direct runoff and recharge implemented in the current ReFH baseflow model (Equation (5)), an increase in routed direct runoff resulting from increased urbanisation will result in an increase in baseflow. However, this is counterintuitive as recharge is most often considered to be reduced as a consequence of increased urbanisation. A more internally logical model structure is therefore suggested where recharge is related to direct runoff from just the rural area $q_t^{(rural)}$, similar to Equation (5). This model formulation has the added advantage that it will ensure a smooth transition between rural and urban catchments. The downside of this model formulation is that the model parameters BL and BR can now only be estimated through optimisation, and not by explicitly fitting the baseflow model.

Model calibration

In the following sections, three variants of the urban extension to the ReFH model (see Table 1) will be tested and compared with the original (rural) version, which makes no allowance for urban effects. The comparison will focus on both model calibration and predictive ability.

The original ReFH model described above has a total of four free parameters: C_{max} (loss model), T_p (routing model), BL and BR (baseflow model). An additional calibration parameter has now been introduced: the ratio of T_p from the urban and rural areas. There are several possible strategies for estimating the model parameters. Previous applications of the ReFH model (Kjeldsen *et al.* 2006; Kjeldsen 2009) fixed the two baseflow parameters, BL and BR, based on separate fitting of the baseflow model to the recession part of the event hydrographs

Table 1 | The four ReFH model variants used in this study

ReFH model variant	Model description
Rural	ReFH with no urban extension
Urban1	ReFH introducing urbanisation into the loss model
Urban2	ReFH introducing urbanisation into the loss model and the routing model
Urban3	ReFH introducing urbanisation into the loss model, the routing model and the baseflow model

followed by optimisation of the loss and routing model parameters (C_{max} and T_p) using an optimisation scheme based on the hill-climbing method of Rosenbrock (1960) to minimise the sum of squares considering all M events jointly, i.e.

$$\text{MSE} = \frac{1}{M} \sum_{m=1}^{M} \sum_{t=1}^{N_m} \left(Q_{t,\text{obs}}^m - Q_{t,\text{sim}}^m \right)^2 \qquad (10)$$

where N_m is the number of observations within the mth event, $Q_{t,\text{obs}}^m$ is observed runoff over time interval t for the mth event, and $Q_{t,\text{sim}}^m$ is the corresponding simulated value.

A second strategy involves estimating the model parameters separately for each event, and then using the average of these individual estimates. The former strategy is likely to yield the most efficient estimates, but there is merit in considering each event separately in order to identify events where model calibration is particularly troublesome. The results reported in this study will be based on simultaneous optimisation across all events, but initial exploratory analysis of the events was conducted as a first step to identify events of insufficient data quality.

STUDY CATCHMENTS

Catchments included in this study represent medium- to larger-scale and vary in size between 39 and 236 km² with a complex mixture of rural and urban land cover (see Figure 2). The catchments were selected on an initial criterion of good-quality rating curves at high flows based
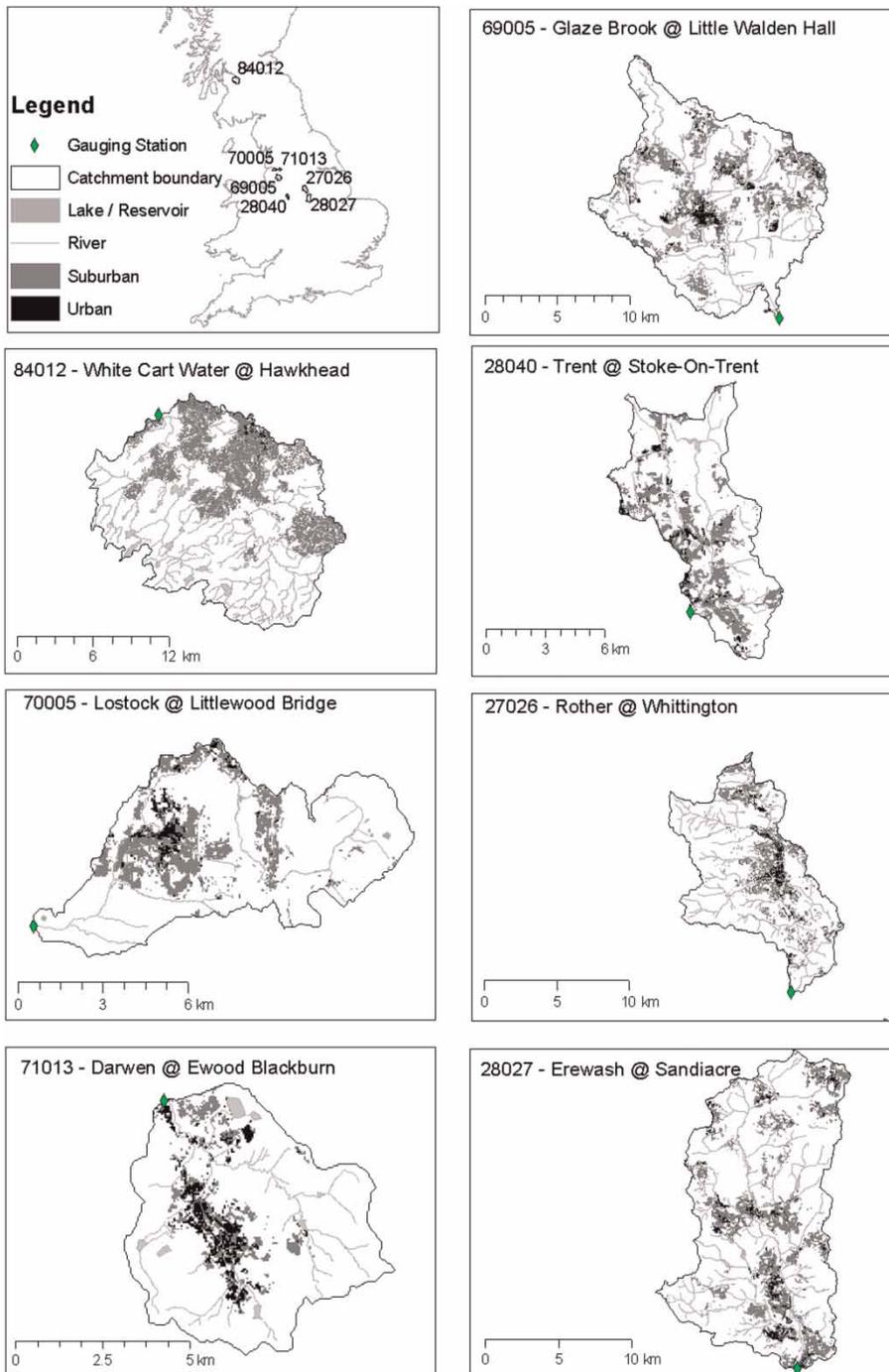
Figure 2 | Map showing urban and suburban land cover in the seven test catchments.

on information provided by the Environment Agency (2010). A second criterion excluded catchments with very permeable soil types, based on values of Base Flow Index (BFI) predicted from Hydrology of Soil Types

(HOST) classes (see Boorman *et al.* 1995). Catchments with BFIHOST values in excess of 0.65 were therefore excluded, as the ReFH model was previously found to perform poorly on such catchments (Kjeldsen *et al.* 2006;

Faulkner & Barber 2009). A third criterion excluded very heavily urbanised catchments ($URBEXT_{2000} \geq 0.6$) for which the assumptions on which the model extensions are built (i.e. the link between urban extent $URBAN_{50k}$ and the $URBEXT_{2000}$ catchment descriptor) are not applicable, as previously discussed. Successful modelling of these catchments is likely to require deployment of detailed hydraulic drainage models, which is beyond the scope of the ReFH model and the improvements suggested in this paper.

The final dataset comprised seven catchments, for which details are shown in Table 2 and locations are shown in Figure 2. The similarity and relatively low values of $URBEXT_{2000}$ of these test catchments is unfortunate, and work to extend the model testing to a greater number of catchments is planned.

Hydrometric data

For the seven catchments, records of sub-hourly flow and both daily and hourly rainfall for all available rain gauges in or close to the catchments were obtained. Based on the method described by Jones (1983) which distributes the daily gauged rainfall by the triangle method, assigning relative weights according to gauge positions within or surrounding the catchment and distributing this total using an averaged profile from hourly gauges, time series of catchment average daily and hourly rainfall were derived for each of the study catchments.

To simulate the evolution of soil moisture prior to each individual flood event, the daily rainfall series were combined with a time series of daily potential evaporation obtained by fitting a six-parameter Fourier series to average monthly values of evaporation obtained from data supplied by the UK Met Office Rainfall and Evaporation Calculation System (MORECS).

Event extraction

From the continuous flow series, individual flood events were identified based on the peaks-over-threshold (POT) series for each flow gauging station record using a threshold set to give, on average, three events per year. For each event, the flow hydrograph and the generating

rainfall event were identified and screened manually to remove events containing suspicious data or events where artificial influences were immediately evident. The period of record and the number of events extracted for each catchment are shown in Table 2. The period of record for which flood events are available was deliberately kept relatively short (between 1990 and 2005 years) to minimise the impact of temporal developments of the urban areas.

COMPARISON OF MODEL VARIANTS

When assessing the performance of different model variants and calibration procedures, the approach taken in this study is to examine the predictive ability of each model. Klemeš (1986) suggested split-sample testing as a means to test the usefulness of models, and it is argued here that the leave-one-out (or cross-validation) technique (Efron & Tibshirani 1993) can be considered as a variant of the split-sample test when applied across events, and it will be used in this study to assess performance and compare model variants.

The performance of three variants of an urban ReFH model have been investigated and assessed against the original rural version of the model (see Table 1). For each model variant, the model parameters C_{max}, T_p and BR were included in the optimisation routine. For the urban model variants 2 and 3, the ratio between the time-to-peak from urban and rural parts of the catchment, respectively, was included. For all model variants the baseflow lag parameter BL was fixed at values obtained from direct analysis of the recession curves of the flood events.

The assessment has been based both on an aggregate measure considering all events, and a more detailed assessment of individual events. Cross-validation is particularly well suited to the evaluation of event-based models as each event can be removed in turn from the calibration dataset and the runoff from this event subsequently predicted using the calibrated version of the model. Consider a catchment where rainfall and runoff data from a total of M distinct flood events are available. The duration of flood event number j is equal to $n^{(j)}$

Table 2 | Summary details of study catchments

Gauge no.	River	Area (km²)	SAAR (mm)	BFIHOST	URBEXT$_{2000}$	Period of record	No. events
27026	Rother	166.76	811	0.491	0.1458	1998–2005	9
28027	Erewash	183.65	709	0.409	0.1548	1992–2004	50
28040	Trent	57.99	861	0.402	0.1566	1990–2004	36
69005	Glaze Brook	160.11	965	0.390	0.1481	1997–2004	22
70005	Lostock	54.50	1021	0.473	0.1472	1990–2001	29
71013	Darwen	39.08	1340	0.424	0.1393	1995–2003	25
84012	White Cart Water	236.24	1306	0.414	0.1276	1990–2001	24

observations, and the contribution to the total cross-validation (cv) statistic from this event is calculated:

$$\mathrm{cv}^{(j)} = \sum_{t=1}^{n^{(j)}} \left(Q_{\mathrm{obs},t}^{(j)} - Q_{\mathrm{sim},t}^{(-j)} \right)^2 \tag{11}$$

where $Q_{\mathrm{obs},t}^{(j)}$ is the observed runoff over the time interval t associated with event number j, and $Q_{\mathrm{sim},t}^{(-j)}$ is the corresponding runoff simulated from the ReFH model using model parameters calibrated using the other M–1 events. The aggregate CV statistic is then finally estimated as the average of the M values of $\mathrm{cv}^{(j)}$. The performance of each of the three urban model variants listed in Table 1 is measured as the proportional change in CV relative to the initial value of CV obtained using the rural model variant, that is

$$\frac{\mathrm{CV}^{(\mathrm{rural})} - \mathrm{CV}^{(\mathrm{urban})}}{\mathrm{CV}^{(\mathrm{rural})}} = 1 - \frac{\mathrm{CV}^{(\mathrm{urban})}}{\mathrm{CV}^{(\mathrm{rural})}} \tag{12}$$

but expressed as a percentage in Table 1. Positive values of this measure suggest an overall improved predictive ability of the urban model variant when compared with the original rural model version, whereas negative values suggest reduced predictive ability. Results obtained for each model variant for each of the seven catchments are shown in Table 3.

The results (Table 3) show that, with two exceptions, the modifications to the loss model (Urban1) only give an increase in performance of between 5 and 8%. The exceptions are 28027 where there was a 2% decrease and 69005 where there was a 32% improvement. With the single exception of 69005, larger improvements arise when both the loss

Table 3 | Performance of urban model variants (% improvement over rural model)

Gauge no.	River	Model variant		
		Urban1	Urban2	Urban3
27026	Rother	5	27	24
28027	Erewash	–2	3	3
28040	Trent	5	22	22
69005	Glaze Brook	32	21	11
70005	Lostock	8	32	29
71013	Darwen	5	26	25
84012	White Cart Water	8	9	7
Average		8.7	20.0	17.3

model and the routing model make allowance for urban effects (Urban2). Finally, it can be seen that bringing in the modification to the baseflow model (i.e. applying all three modifications) (Urban3) does not yield any further improvement and, in most cases, causes slightly poorer performance than Urban2. The reason for this deterioration in model performance when moving from Urban2 to Urban3 is not clear, but it is apparent from the subsequent discussion that, for each catchment, the between-event variability is large which might lead to unexpected results and mask differences in performance between model types. However, applying model variant Urban3 still represents a good improvement on the original model (an average improvement of 17%) and, given the better logical structure of the revised baseflow model, Urban3 is the preferred choice.

A more detailed breakdown of the model performance is presented in Figure 3 showing the individual values of $\mathrm{cv}^{(j)}$ for the different models as well as the summary statistics in the form of box-plots. In Figure 3, values of $\mathrm{cv}^{(j)}$
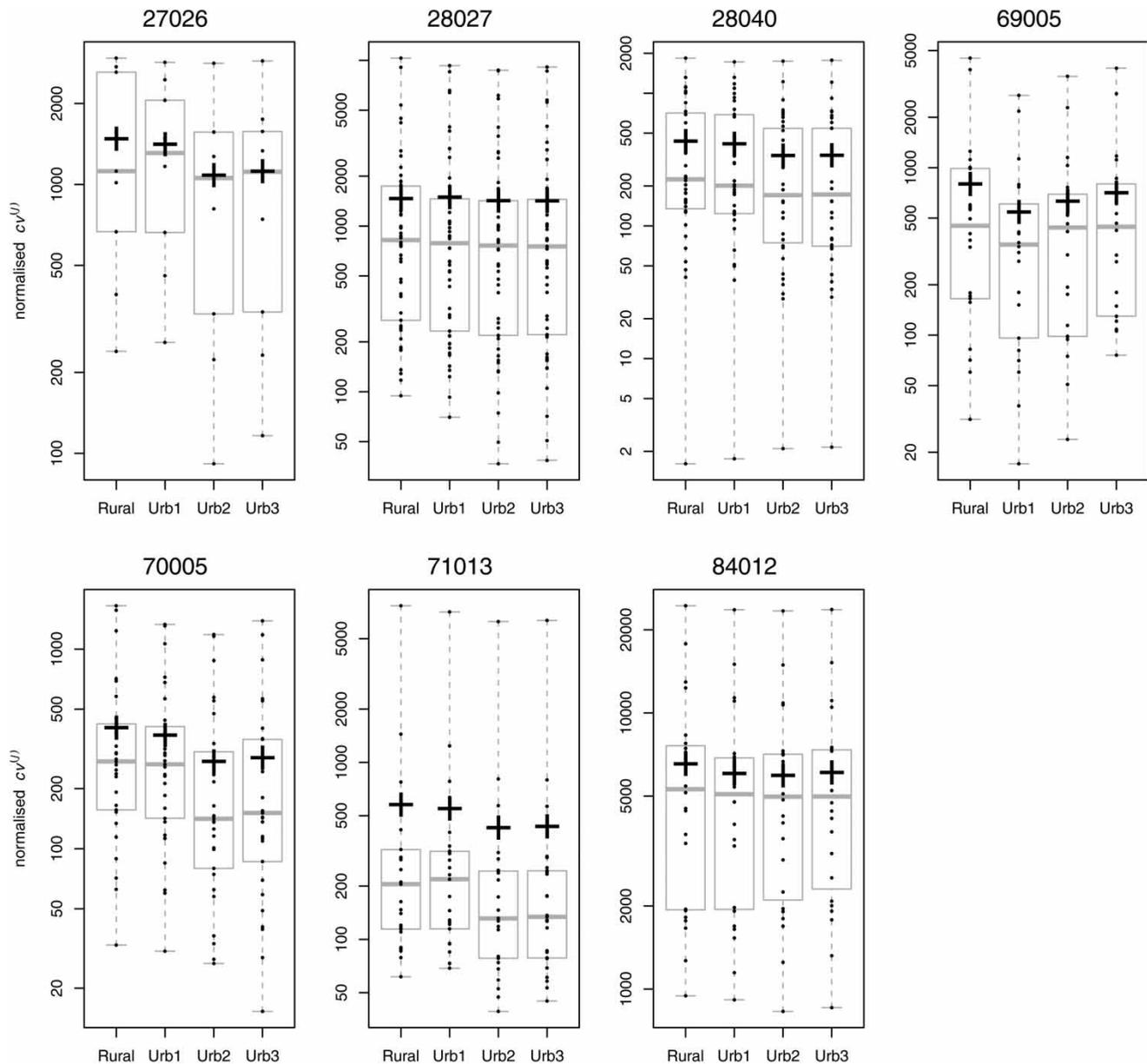
Figure 3 | Comparison of normalised cross-validation statistics (mm^2 h^{-2}) for individual events cv$^{(j)}$ for all catchments and for all model variants. Box-plot shows the 75, 50 (median) and 25% quantiles, as well as the maximum and minimum values. The corresponding mean values are indicated with a $+$ symbol.

have been normalised to units of mm^2 h^{-2} by dividing by catchment area.

The plots in Figure 3 suggest that the improvements reported in Table 3 should be viewed alongside the large variability of model performance between events. Further, the distribution of performance for all catchments is skewed by a few events where the model did not perform well. This asymmetric performance across events is also

evident from Figure 3 where the mean values are generally larger than the corresponding median values. This suggests that poor performance recorded on individual events might dominate the summary statistics in Table 3 by masking overall improvement obtained for the bulk of the events.

The largest improvement in model performance is obtained when introducing separate routing from the

Table 4 │ Median of rural time-to-peak (hours) and ratio between urban and rural time-to-peak estimated from each of cross-validation dataset

Gauge	Rural T_p	Urban1 T_p	Urban2		Urban3	
			T_p	Ratio	T_p	Ratio
27026	4.23	4.32	6.84	0.28	7.13	0.28
28027	12.82	12.66	16.32	0.53	17.03	0.51
28040	1.85	2.41	6.68	0.18	6.94	0.19
69005	3.65	4.36	9.91	0.30	10.22	0.30
70005	4.50	4.47	6.13	0.26	5.57	0.28
71013	1.20	1.09	1.97	0.24	2.09	0.23
84012	5.22	5.24	6.01	0.59	6.21	0.55

rural and urban areas of the catchment. To illustrate the impact on the model parameters of the routing model, Table 4 shows the time-to-peak for the rural parts of the catchment and the corresponding ratio between time-to-peak for the urban and the rural areas. The estimates quoted in Table 4 are the median values of the M estimates obtained for each catchment as part of the cross-validation exercise. Note that the ratio between time-to-peak for urban and rural parts of the catchments only applies to model variants Urban2 and Urban3.

For all catchments, the introduction of separate routing from the rural area has increased the time-to-peak when compared to the single unit hydrograph used in model variants Rural and Urban1. Similarly, the estimated ratios suggest that the urban areas have time-to-peak values lower than the initial estimates from Rural and Urban1. These results suggest that applying a single unit hydrograph to an urban catchment does not adequately capture the combined effect of mixed urban–rural land cover.

Towards application in ungauged catchments

In order for the extended model (Urban3) to be applicable in ungauged sites, it will be necessary to provide a method linking the ratio between the time-to-peak values from the urban and rural parts of the catchment to one or more catchment descriptors. It will be reasonable to expect that this ratio is largely controlled by the urban land cover and, in particular, the location of the urban areas within the catchment. For example, a more distinct response from an urban area might be expected if it is

located in the lower part of the catchment close to the gauging station, rather than a similar urban area located in the upper parts of a catchment where channel attenuation of the flow response will mask the distinct urban response. Figure 4(a)–(c) shows the values of the T_p ratio for Urban3 (see Table 4) plotted against three indices describing different aspects of the spatial geometry of urban land cover: the extent (URBEXT), the location (URBLOC) and the concentration (URBCONC) of urban land cover.

The plots in Figure 4(a)–(c) suggest that it might be feasible to try to develop a general relationship between the T_p ratio and the index of urban concentration (URBCONC), which is derived based on a 50 m gridded land cover dataset as the mean drainage path length of all cells characterised as urban to the catchment outlet. There appears to be little relationship between the T_p ratio and the other two indices URBEXT and URBLOC. In general, catchments with high values of urban concentration (URBCONC) are most often associated with heavily urbanised catchments (Figure 4(d)). This would support the intuitive reasoning that the ratio between T_p values should increase in catchments with more contiguous urban areas. However, based on data from seven catchments it is difficult to provide a more authoritative statement.

Event-specific performance

The ReFH model was developed as a relatively simple lumped conceptual model; it is therefore inevitable that there will be errors resulting from the application of a simple model structure to a wide range of catchments and hydrological conditions. In this section, the performance of the ReFH model is assessed on individual events conditional on event characteristics including initial soil moisture condition and rainfall event characteristics such as depth, duration and intensity. The influence of these factors is investigated by studying the relative cross-validation statistics associated with each individual event by considering the $cv^{(j)}$ values from the rural and urban models as

$$\frac{cv_{rural}^{(i)} - cv_{urban}^{(i)}}{cv_{rural}^{(i)}} = 1 - \frac{cv_{urban}^{(i)}}{cv_{rural}^{(i)}} \qquad (13)$$
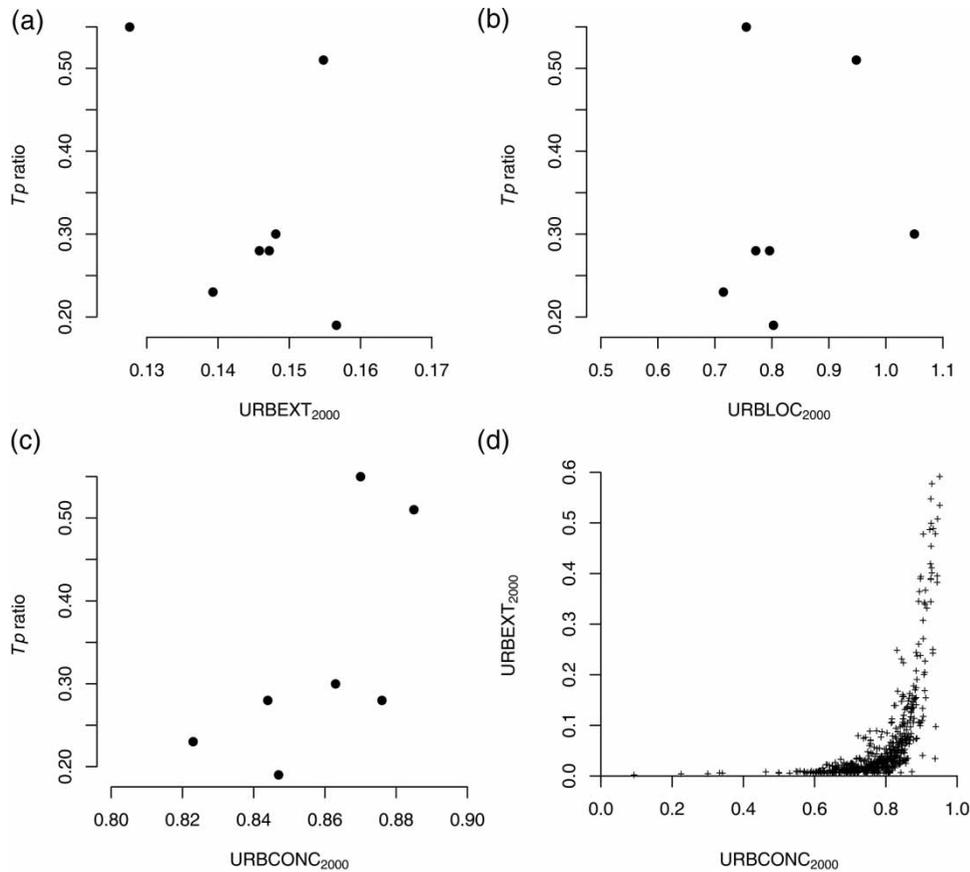
Figure 4 │ Ratio of T_p between urban and rural parts of catchments plotted against urban extent (URBEXT), urban location (URBLOC) and urban concentration (URBCONC) as derived from land cover 2,000 maps (CEH 2009). URBEXT$_{2000}$ plotted against URBCONC$_{2000}$ for 565 catchments in the HiFlows-UK database.

and plotting this event-specific performance measure against the event characteristics. A simple linear regression model was estimated by ordinary least squares for each catchment, describing the relative cross-validation statistics in Equation (13) as a function of individual event characteristic. The resulting r^2 coefficient of determination values was reported as an additional measure of relationship between the two variables.

Only the results from the Urban3 model variant are reported here as this is considered the most promising model variant considering performance and internal logic.

Initial soil moisture

The soil moisture state of the catchment at the onset of the storm event is clearly a very important factor in controlling

the catchment flood response in most UK catchments, and is included in the loss model in Equation (1) as C_{ini}. Figure 5 shows the event-specific performance measure, Equation (13), for the Urban3 model variant plotted against the corresponding value of C_{ini}/C_{max} for each event and for each catchment. The outermost convex hull has been drawn around each of the datasets to assist in the visual interpretation of trends or patterns in the dataset. The plots suggest that variability in model performance between events is too large to identify specific effects. The r^2 values also suggest a generally weak or non-existent relationship between initial soil moisture and model performance.

Storm characteristics

Figure 6 shows the event-specific performance measure, Equation (13), for the Urban3 model variant plotted
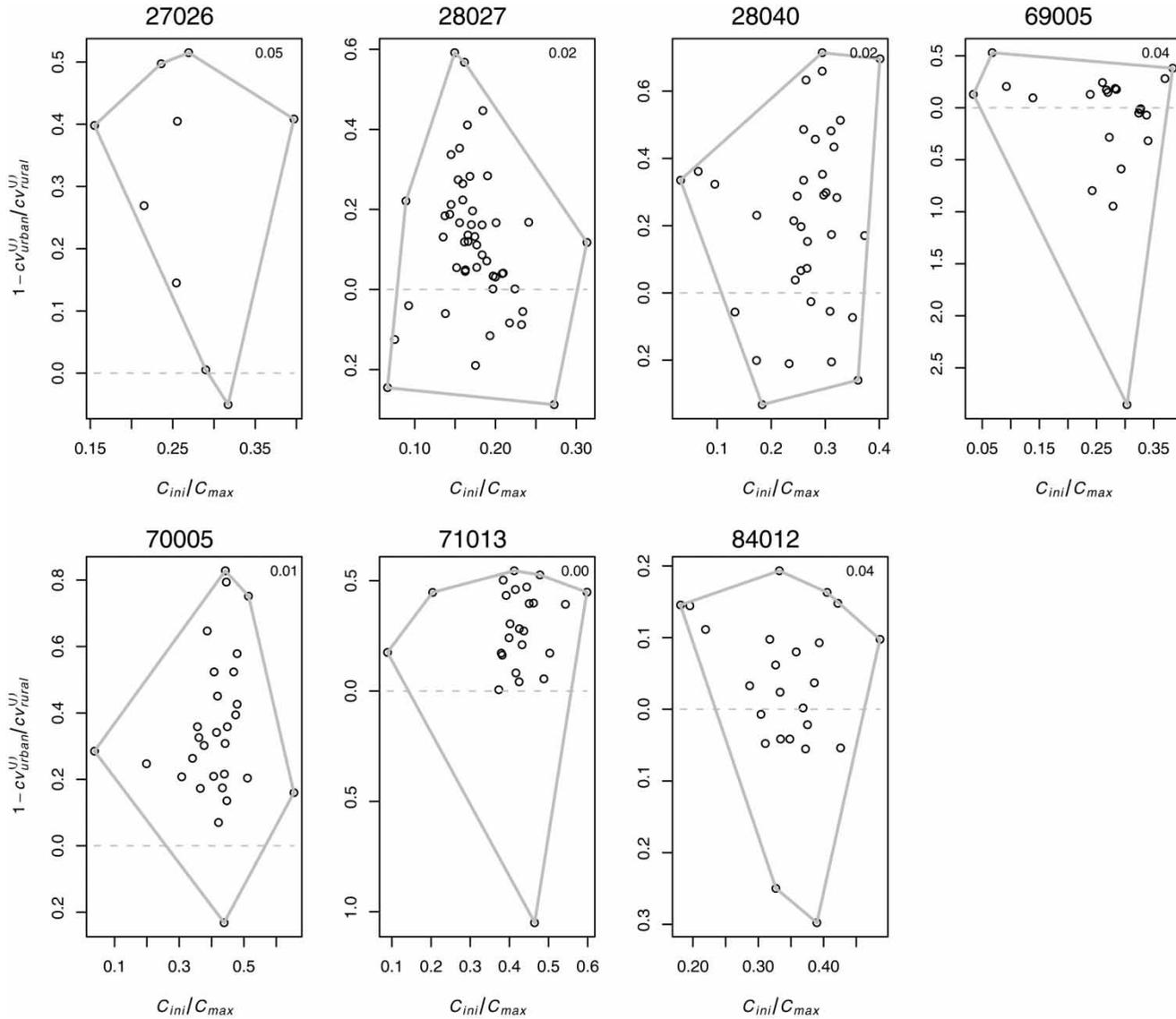
Figure 5 │ Plot of relative cross-validation statistics (Equation (13), percentage improvement over original model) against initial soil moisture content C_{ini}/C_{max} for model Urban3. Number in upper right corner of each plot is the r^2 coefficient of determination value obtained through linear regression.

against the storm characteristics of duration, depth and average intensity. Regarding initial soil moisture, the variability in model performance between events as well as between catchments appears to mask any consistent trend in model performance, resulting from an inability to model storms with specific characteristics. Again, the low r^2 values suggest no or little relationship between the storm characteristics and model performance.

IMPLICATIONS FOR DESIGN FLOOD ESTIMATION

As mentioned previously, the ReFH model is routinely used in the UK for simulation of design flood hydrographs (Faulkner & Barber 2009). If the extended urban ReFH model (Urban 3) is to be adopted for more general use, it is however necessary to ensure that the design model provides estimates that are in line with the expected impacts of urban development.
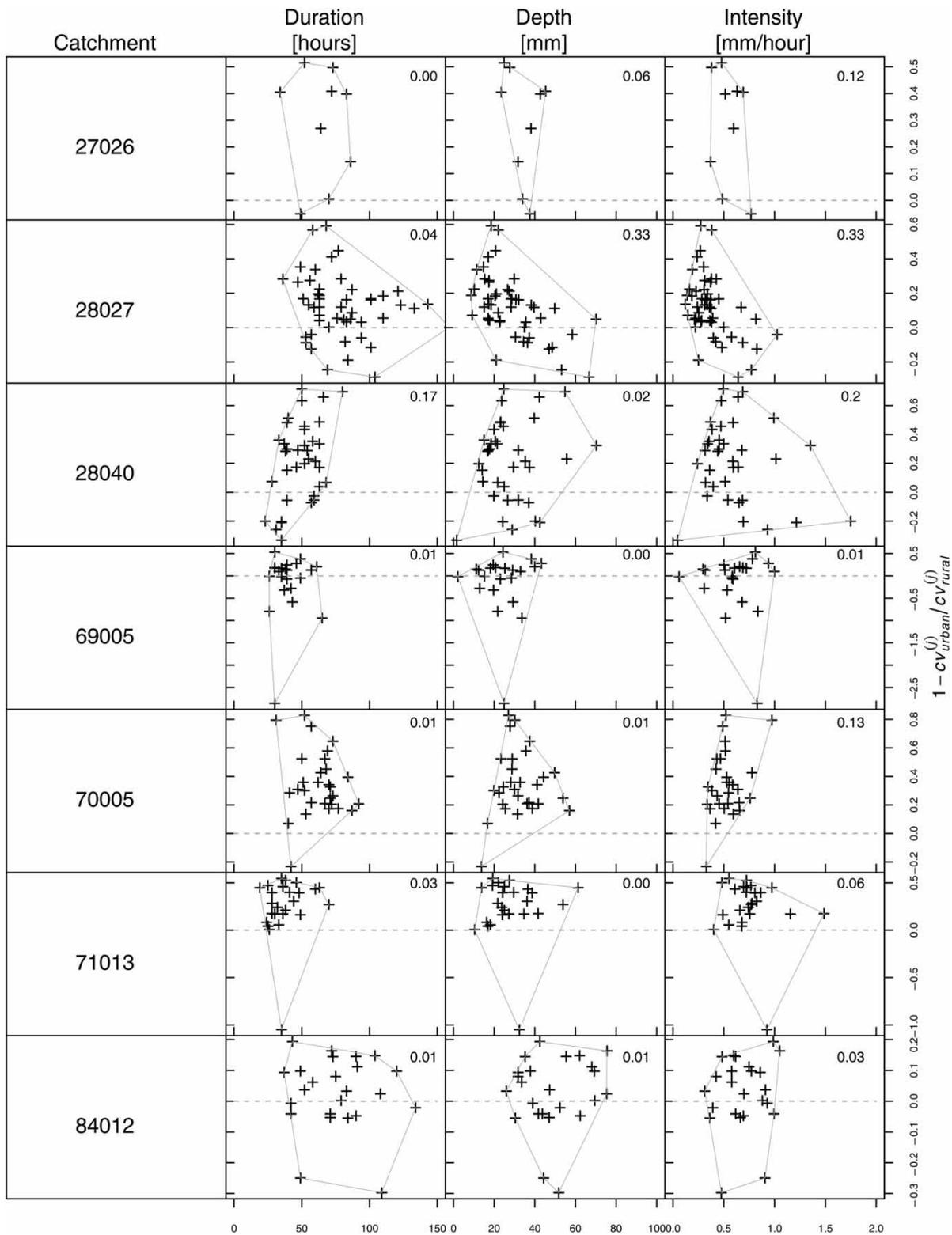
Figure 6 │ Plot of relative cross-validation statistics (Equation (13), percentage improvement over original model) against storm characteristics (duration, depth and intensity) model Urban3. Number in upper right corner of each plot is the r^2 coefficient of determination value obtained through linear regression.

The effects resulting from the introduction of a more explicit consideration of urban land cover into the ReFH model are illustrated by comparing design flood hydrographs generated using two different model variants (Rural and Urban3) on a 60 km^2 rural catchment located in Eastern England (30004). The default ReFH model parameters for the catchment draining the River Lymn down to Partney Mill (gauging station no. 30004) are shown in Table 5.

First, a 100-year design hydrograph is simulated for the catchment in a rural state by following the procedures described by Kjeldsen *et al*. (2006) using pre-specified design values of initial soil moisture (C_{ini}), a 100-year design rainfall event (duration, depth, return period and temporal profile), a value of initial baseflow and ReFH model parameters derived from catchment descriptors. Next, corresponding 100-year design flood hydrographs are simulated for the same catchment by the Urban3 model using a range of values of URBEXT$_{2000}$ and the ratio of T_p from urban and rural parts of a catchment. The predicted effects of introducing urban land cover on the design flood hydrographs are illustrated in Figure 7(a) and (b). While Figure 4 showed that it is not yet possible to derive an authoritative link between urban land cover and the ratio between T_p values, it is assumed here that increased urbanisation will lead to an increasing distinction between routing times for rural and urban parts of the catchment.

Figure 7(a) shows the 100-year design hydrograph simulated by the Rural model as a black line. The corresponding 100-year design hydrographs generated from the Urban3 model with a fixed value of URBEX$_{2000}$ of 0.200 are represented by grey lines indexed as 1, 2 and 3, representing different values of the ratio between urban and rural T_p values equal to 1, 0.5 and 0.25. A value of 1 for the T_p ratio represents the situation where a similar IUH is used for both the rural and urban parts of the catchment.

Next, Figure 7(b) shows the 100-year design hydrograph generated by the rural model compared to the corresponding design flood hydrographs generated from the Urban3 model with a fixed ratio between T_p values of 0.5 and values of URBEXT$_{2000}$ of 0.125, 0.20 and 0.40, representing increased levels of urbanisation. In both Figure 7(a) and (b), it can be observed that the impacts of increased urban development is to shorten the response time of the catchment and to increase the peak flow. The values of URBEXT$_{2000}$ and the T_p ratio used in the sensitivity analysis are representative of the typical range values for which the ReFH model would be used in practical application. The behaviour of the Urban3 model shown in Figure 7(a) and (b) is considered reasonable and in line with the expected impacts of increased urbanisation (increased peak flow and reduced response time) as discussed in the introduction.

DISCUSSION AND CONCLUSIONS

This study has tested a number of possible extensions to an existing rainfall–runoff model (ReFH) to explicitly allow for the effect of urban land cover on catchment flood response. The extensions suggested here have all been specifically designed to align with a national dataset of urban land cover (URBEXT$_{2000}$) routinely used in flood modelling and readily available on the FEH CD-ROM (CEH 2009). While this is helpful because it could help the transfer of results to the realm of applied hydrology in the UK, it is recognised that it could have constrained the investigation to a suboptimal set of possible extensions.

Despite this limitation, the results presented here suggest that explicit consideration of urban land cover improves the predictive ability of the ReFH model. No formal statistical test for the significance of the improvements was offered. However, for all three urban model variants an increase in predictive ability was recorded on all selected catchments with the exception of one (28027), where introduction of urban land cover into the loss model (Urban1) resulted in a 2% reduction in predictive ability.

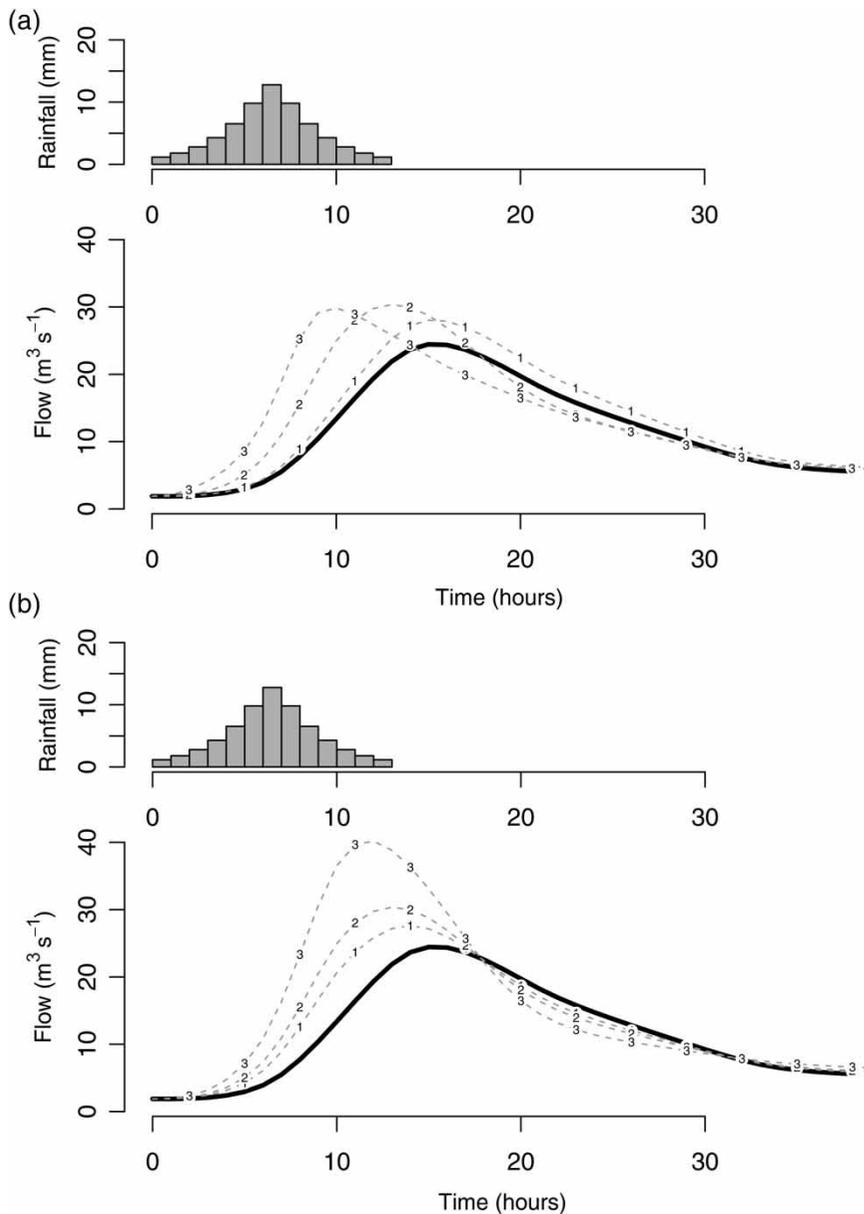From a more detailed breakdown of the model performance for individual events it is clear that the average

Table 5 | ReFH model parameters for catchment 30004 (from catchment descriptors)

ReFH model parameter	Unit	Estimate
Baseflow lag, BL	Hours	58.4
Baseflow recharge, BR	–	1.31
Maximum soil capacity, C_{max}	Millimetres	471
Time to peak, T_p	Hours	7.31

Figure 7 │ Design flood hydrographs with a 100-year return period generated by the Rural model (black) and the Urban3 model for (a) $URBEXT_{2000} = 0.200$ and T_p ratio values of 1.0 (index 1), 0.5 (index 2) and 0.25 (index 3); and (b) T_p ratio of 0.50 and $URBEXT_{2000}$ values of 0.125 (index 1), 0.20 (index 2) and 0.40 (index 3).

improvement (as measured by the CV statistic) should be viewed in the context of large between-event variability in model performance for all model variants (rural and urban). This suggests that factors other than urban land cover exhibit more control over model performance for individual events. The study found no obvious relationship between model performance and event characteristics, considering both initial soil moisture and storm characteristics

(depth, duration and intensity). It would therefore be logical to look for factors not captured by the lumped model, for example, the spatial distribution of rainfall and soil moisture. A logical next step would be to consider a spatially distributed model, which would also enable a geometric representation of the urban land cover rather than the lumped indicative value used in this study. However, further research and model development is required to

determine if the introduction of a distributed (or gridded) model will lead to sufficient improvement in predictive ability to warrant the additional efforts required for routine model application.

The seven catchments used in this study constitute a subset of urban catchments in the UK where good-quality hydrometric flood data are available. The extent of urban land cover, as quantified by URBEXT$_{2000}$, is close to 15% on all of the seven catchments. These catchments represent a subset of catchments where the ReFH model in its current form can be applied with some confidence, i.e. catchment with BFIHOST values less than 0.65 and URBEXT$_{2000}$ less than 0.60. Further research and model development is required for further generalisation of the ReFH model to provide reliable results on these types of catchments.

Despite the caveats discussed above, the results presented in this paper still show an increase in predictive ability when modelling the flood response from catchments with a mixture of rural and urban land cover. In addition, it was demonstrated that the design flood hydrographs simulated from the extended model contrasts the rural response from the same catchment in an expected form, i.e. increased peak flow and reduced response time. There is therefore a case for moving towards more routine use of this extended ReFH model structure, noting that the ReFH model is widely used in UK flood studies. A particular problem is that while the extension to the loss model was introduced without a need for additional model calibration, the extra parameter required for use of the urban routing model needs to be related to catchment descriptors before the model can be applied to ungauged catchments. This is likely to require the extended ReFH model to be calibrated on more urban catchments before such relationships can be reliably established, e.g. through a regression model for estimating the ratio between T_p parameters from catchment descriptors.

In this study, an assumption of 30% imperviousness of an urban area was used in Equation (8) based on recommendations from Packman (1980) derived from analysis of observed flood data. More contemporary research into the impervious fraction of urban areas from Belgium using remote sensing imagery suggests that values can vary significantly depending on the site and over time. Chormanski *et al.* (2008) observed impervious fractions of 0.44–0.46 for an urban area of Brussels, while Dams *et al.* (2012) found an increase from 0.24 to 0.29 during the period 1986–2003 within the Kleine Nete catchment. These values are not too different to the 30% used in this study (Equation (8)) but highlight the possibility for utilising information from aerial photos to provide contemporary values for different urban land use types. Such values are of considerable use in modelling flooding from modern urban areas due to the increasing use of sustainable urban drainage systems (SUDS) to facilitate infiltration and, conversely, the potential decrease in infiltration though loss of pervious surfaces caused by urban creep.

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