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Design flood estimation and utility of high-resolution calibration data in small, heavily-urbanized catchments

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ABSTRACT

Design flood estimates are often required for small, heavily-urbanized catchments, which respond quickly to storm events. However, hydrological models are most frequently calibrated using daily or hourly data on larger, more rural catchments, which respond on much longer timescales. Here, we calibrate a lumped, conceptual rainfall-runoff model (ReFH2) in three small (2-6 km^2), heavily-urbanized catchments in Swindon, UK, assessing the benefits of using high-resolution temporal and spatial data. Modelling shows that heavy urbanization does not by itself invalidate the applicability of a lumped, conceptual model. However, we find great dissimilarities between runoff behaviour in different heavily-urbanized catchments, with some types behaving similarly to rural catchments. In other cases, response and contributing catchment area can depend more on underground topology than catchment topography. Calibrated runoff response is insensitive to the temporal resolution of the calibration events in all study catchments. Future research should aim to differentiate between different types of heavily-urbanized catchment, potentially through landscape metrics to measure the connectivity and isolation of different land surface types.

KEYWORDS

design flood estimation, rainfall-runoff, urbanization, ReFH, hydrological modelling

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INTRODUCTION

Catchment urbanization reduces infiltration capacity, reduces surface roughness, increases overland flow and reduces the distance that runoff must travel to reach a watercourse (Redfern *et al.* 2016), resulting in increased runoff volume (Leopold 1968; Valtanen *et al.* 2013), increased peak flow (Hall 1977; Braud *et al.* 2013), flashier response and reduced response time to rainfall (Anderson 1970; Laenen 1983; Granato 2012). Extreme rainfall events are therefore more likely to result in both pluvial and fluvial flooding (Konrad 2014).

In the absence of long-term flow data, design flood estimation underpins the engineer's ability to estimate the flood peaks, hydrographs and extents required for a multitude of engineering, planning and insurance purposes, including the design of urban drainage systems and flood defences. Estimation methods fall into two broad classes: statistical (e.g. Kjeldsen *et al.* 2008; Shu & Ouarda 2008; Guse *et al.* 2010) and process-based (e.g. Kjeldsen 2007; Buytaert & Beven 2011), including approaches that are a combination of both (e.g. Eagleson 1972; Franchini *et al.* 2005; Iacobellis *et al.* 2011). Statistical analysis can be considered the "standard approach" to flood frequency estimation (Klemeš 1993). However, process-based, event-based rainfall-runoff modelling, estimating an output runoff hydrograph from an input rainfall hyetograph and assumptions about antecedent catchment wetness, can be preferable in several situations. Firstly, rainfall-runoff modelling utilizes rain gauge data records, which are typically longer and spatially denser than records from flow monitoring stations, so it is preferable whenever estimates are required for very long return period events (Faulkner & Barber 2009; Blöschl *et al.* 2013). Secondly, rainfall-runoff methods allow the effects of changing land use or climate to be investigated by varying model parameters or inputs (Faulkner & Barber 2009), making them particularly useful for comparison of pre- and post-development runoff (e.g. Miller *et al.* 2014). Thirdly, and perhaps most importantly for small urban catchments, rainfall-runoff models can be used to provide flow-time input boundaries to hydrodynamic models for flood risk mapping (e.g. Environment Agency 2013) and for the design of flood alleviation (e.g. Royal Haskoning 2010) and other schemes (e.g. Ghimire & Jones 2014).

While design flood estimation is a mature topic, there is limited literature on the particular challenges posed by small, heavily-urbanized catchments, and specifically on the use of high-resolution temporal data to overcome modelling challenges related to rapid flood response to rainfall, as most models applied at a national scale are calibrated using daily or hourly data obtained from national monitoring networks biased towards more rural catchments (e.g. Quintana Seguí *et al.* 2009, France; Markstrom *et al.* 2015, USA; McMillan *et al.* 2016, New Zealand). In the UK, both rapid urban growth, driving expansion and intensification of urban areas, and climate change, predicted to result in larger one-hour peak rainfalls (Kendon *et al.* 2014), have been identified as drivers of future urban flood risk (Evans 2004; Evans *et al.* 2008). This combination of factors requires consideration of the suitability and accuracy of design storm models when applied in small urban areas, which will likely be highly affected by changes to peak rainfall intensity.

The purpose of this study is to assess the performance of a lumped rainfall-runoff design-flood model in small, heavily-urbanized catchments, and assess the potential benefits of using high-resolution data in calibration. For this, we use ReFH2 (Kjeldsen *et al.* 2013; Wallingford HydroSolutions 2015) and flow data from three case study catchments. ReFH2 is a lumped, conceptual rainfall-runoff model used widely for design flood estimation in the UK (SEPA 2015; Wallingford HydroSolutions 2015), including in small urban catchments (e.g. Intertek Energy & Water Consultancy Services 2015, RSK Land & Development Engineering Ltd. 2016), and is integrated with commerical tools to provide design flow-time input boundaries to detailed hyrdrodynamic models, corresponding to upstream catchment response to design rainfalls of specified return periods. . The results of this study are used to outline and refine recommendations for best practice and to identify next steps for ongoing development of design flood estimation to cope with future urban expansion.

STUDY CATCHMENTS

Three small, heavily-urbanized catchments (Table 1), all located within the River Ray catchment to the north of Swindon town centre, UK (Figure 1), were used as study catchments. Swindon has relatively dry and sunny summers for the UK, with approximately 50-60 mm mean monthly rainfall and 150-210 mean monthly sunshine-hours during April-September 1981-2010 (Met Office 2014). Over the same period, mean monthly October-March rainfalls and sunshine-hours were approximately 50-80 mm and 60-115 hours respectively.

In all three catchments, drainage paths are heavily altered from their natural states. The FEH Web Service (CEH 2015) delineates catchments using natural drainage pathways based on a 50-metre digital elevation model (DEM). This estimates area well for the Rodbourne catchment, but is unable to delineate the natural Haydon Wick Brook catchment into its artificially-drained northern section, HWN, and its surface-channel-drained southern section, HWS. Catchment area and drainage path slope can therefore be calculated from a combination of DEM, topographic (TOP) and storm drainage mapping (SD). Applying urban drainage and topographic mapping after Miller & Grebby (2014) reduces the total area of Haydon Wick Brook relative to that derived from the 50-metre DEM. However, the area of Rodbourne increases significantly when using 10-metre DEM data and merging catchment boundaries to delimit natural drainage boundaries (Table 1). Mean drainage path slope is only slightly affected by mapping method and ranges from 14.0 m/km (Rodbourne) to 40.6 m/km (Haydon Wick North).

Soil types vary between the three catchments: Haydon Wick South and Haydon Wick North overlie slowly-permeable, seasonally-wet loamy and clayey soil, while Rodbourne overlies both this and freely-draining, shallow, lime-rich soil in approximately equal measure (Cranfield University 2017). However, Haydon Wick has the highest BFIHOST (baseflow index estimated from soil data), reflecting the 1-km resolution of the soil maps underlying the FEH Web Service and the outline of the Haydon Wick catchment advancing into squares of more permeable soil to the east.

Urban cover fractions for the study catchments were calculated as a weighted total of urban and suburban land cover class extents derived from recent Land Cover Mapping (LCM) using remote sensing imagery (Rowland *et al.*, 2017). The methodology used for deriving $URBEXT_{2000}$ (Bayliss *et al.* 2006) was used to derive $URBEXT_{2015}$, defined here as an equivalent index of catchment urban extent for the year 2015. While URBEXT has clearly increased in both Haydon Wick and Rodbourne over the period 2000-2015, the different methods for estimating storm drainage area (topographic and 10-metre DEM) do not estimate significantly different $URBEXT_{2015}$ values.

It should be noted that the surface water drainage network shown on Figure 1 does not detail connections to individual buildings or some large industrial/commercial areas; this is most clear for the highly urbanized areas in the upper reaches of Rodbourne. Further information on these catchments can be found in Miller & Hess (2017), where they are catchments S3, S4 and S5.

Haydon Wick Brook and the Rodbourne stream were identified as sources of fluvial flooding during the July 2007 floods. In response to these floods, Haydon Wick Brook was subject to a flood risk assessment (Royal Haskoning 2010) and subsequent alleviation scheme, completed in 2013. Flood peaks and volumes were estimated using both the improved FEH statistical method (Kjeldsen *et al.* 2008) and the FSR/FEH rainfall-runoff method (Houghton-Carr 1999). ReFH2 did not exist at that time and the original version of ReFH (Kjeldsen 2007) was not used as it is not recommended for use in urban catchments. The alleviation scheme consists of sheet piling, installed along 2 kilometres of the brook, together with new embankments and bridge replacement. It is intended to protect against the 1-in-100 year flood with a 20% climate change allowance. For comparison with this study, the hydraulic model used in the assessment and design of the Haydon Wick Brook flood alleviation scheme was calibrated against rainfall and stream depth data both recorded within the catchment at 2-minute resolution, but only over a period corresponding to a single summer event (3rd June 2008).

EVENT SELECTION

Catchment flows were recorded at 5-minute resolution using ultrasonic Doppler shift instruments (Unidata Starflow 6526H), with velocity and depth accuracy of ±2% and ±0.25% respectively, mounted to the bed of suitable hydraulic structures, according to ISO (2010), in accessible culverted channel locations. Monitoring was conducted from April or May 2011 to October 2015. Depth and velocity data were quality controlled and processed according to the method outlined by Blake & Packman (2008), using measured cross-sections to derive flow. Ratings developed from spot-gauging of depth and flow, using a SonTek FlowTracker, were used to calibrate depth and velocity observations across the channel cross-section, and increase accuracy. Rainfall at 15-minute resolution was made available from an Environment Agency tipping bucket rain gauge at Swindon sewage treatment works, with a tip resolution of 0.2 mm, located no more than 5 kilometres from the furthest point in any study catchment.

The study rain gauge record was discretized into single events for the common period of flow records from May 2011 to October 2015. Events are defined as periods in which 2 or more mm of rainfall are observed, bookended by antecedent and post-event dry periods. The post-event dry period is defined as a 12-hour period having zero rain during the first 6 hours and no more than 2 mm of rain in the subsequent 6 hours. The antecedent dry period is defined as a 12-hour period having no rain in the two hours before the start of a rainfall event and no more than 2 mm of rainfall across the whole 12-hour period.

After defining 321 events in total, 38 were selected for model calibration. These were events for which

- the rainfall hyetograph was single-peaked,
- the corresponding runoff hydrographs were all single-peaked,
- rainfall-generated runoff was zero at the start of the event, and
- runoff returned to baseflow conditions before the start of the next event.

Table 2 summarizes the 38 selected rainfall events, showing that all are relatively frequent. This is not unexpected, due to the short length of the monitoring period and stringent selection criteria that rejected 88% of recorded events.

The seasonality of the 38 calibration events, shown in Figure 2, indicates that they are spread reasonably evenly throughout the summer and first half of winter, with a majority occurring during May-October, and a mean occurrence in mid-September. The comparative lack of calibration events in the second half of winter reflects the tendency for rainfall during this time to be frontal, rather than convective, consisting of long duration, low-intensity rainfall, rather than the higher-intensity, shorter duration, clear and discrete rainfall events that would be ideal for model calibration. Table 3 summarizes the mean values of calibration event rainfall-runoff metrics for each site, revealing that ROD and HWS have similar rainfall-runoff responses. However, Figure 2 shows that flow profiles in HWS are considerably smoother than in ROD, potentially as a result of the lower urbanization fraction or the influence of the large, contiguous green area. The rainfall runoff response in Haydon Wick North (HWN) is clearly different, with much higher peak flows and shorter response times across all time-based metrics, however the percentage runoff is similar to ROD and HWS. This may indicate that not all the runoff from pervious areas in the upper HWN catchment is received by the drainage network.

REFH2 MODEL OVERVIEW

ReFH2 (Kjeldsen *et al.* 2013; Wallingford HydroSolutions 2015) is an event-based, lumped, conceptual, time-series rainfall-runoff model, whose parameters can either be fitted to at-site calibration events or, for ungauged catchments, estimated through regression relationships with catchment properties. It consists of three model components: loss model, routing model (unit hydrograph) and baseflow model (Figure 3). ReFH2 is of particular importance in the UK, as it is the latest version of the ReFH method (Kjeldsen 2007), which is widely used for design flood estimation in the UK. It addresses some criticisms of the original ReFH model (Faulkner & Barber 2009) through: i) explicit separation of urban and rural fractions within the model structure, ii) a far larger data set of calibration catchments, including more permeable catchments and iii) an updated design rainfall model (Stewart *et al.* 2014). Recent research into estimation of the median annual flood in small catchments (Faulkner *et al.* 2012a; Faulkner *et al.* 2012b) has found that older and simpler methods designed specifically for small catchments, such as IH124 (Marshall & Bayliss 1994), tend to give larger and more biased errors than modern methods descended from the Flood Estimation Handbook (FEH: IH 1999). It is noted that ReFH2 had not yet been developed at the time of that research, although ReFH was a tested FEH method.

DISCUSSION: MODEL CALIBRATION

IN GAUGED CATCHMENTS

Calibration was undertaken at both a 15-minute resolution and at an aggregated 1-hour resolution, to allow comparison between the higher-resolution calibration and one performed at the same temporal resolution used in developing the ReFH2 model. The baseflow model is a linear reservoir controlled by BL, a recession constant, and BR, the ratio of baseflow recharge to runoff. In this study, BL and BR were calibrated simultaneously using the ReFH2 Calibration Utility (Wallingford HydroSolutions 2016a). Zero baseflow was assumed in HWN, as the monitoring equipment recorded only insignificant and zero dry-weather flows. C_{ini}, the initial soil moisture content, was estimated from a daily rainfall record at the study rain gauge using the ReFH2 Calibration Utility.

Each catchment's urban fraction was set equal to the $URBEXT_{2015}$ value reported in Table 1 for topographic mapping and, based on the results of earlier topographic mapping of these same catchments (Miller & Grebby 2014), the whole urban fraction delineated in this way was considered nominally impervious (IF = 1). This is considered reasonable, as the 10-metre resolution of the mapping limits the amount of aggregation of different land types occurring in each pixel, ensuring, for example, that gardens are not absorbed into urban areas. In this interpretation, the impervious area's fixed runoff fraction (IRF) represents any loss of rainfall landing on the impervious area, whether these losses occur in the "impervious" area (e.g. through surface cracks) or not (e.g. because of infiltration in a rural zone located between the impervious area and watercourse). Hence, IRF acts to relate effective to total impervious area, and depends strongly on the spatial configuration of urban areas within the catchment. Maximum soil moisture capacity (C_{max}) and IRF are both strong controls on percentage runoff, and therefore flood peak magnitude, so many very different combinations of both can result in the same peak flow. Furthermore, rural unit hydrograph time-to-peak, T_p, is sensitive to IRF because higher IRF values reduce losses and increase the proportion of total rainfall routed via the urban unit hydrograph (whose time-to-peak is expressed as a fraction of T_p). Hence, rather than joint calibration of C_{max}, T_p and IRF, C_{max} and T_p were optimized jointly to minimize the mean error in peak flow magnitude and timing across all 38 calibration events, for fixed values of IRF. The T_p-ratio of the urban unit hydrograph to the rural unit hydrograph was left at its default value of 0.5, due to the lack of information on how to relate it to catchment characteristics, beyond preliminary reporting by Kjeldsen *et al.* (2013) and Wallingford HydroSolutions (2015). However, as this controls the peakedness of urban runoff, it is clear that different combinations of T_p and T_p-ratio can achieve similar runoff profiles. For all catchments and events, BF_0, the initial baseflow rate, was derived directly from gauged data as the flow rate at the start of the rainfall event.

IN UNGAUGED CATCHMENTS

In the absence of monitored flow data, regressions on FEH catchment descriptors are used to estimate parameter values and initial conditions for ReFH2. The forms of these equations, showing the specific catchment descriptors used, without regression constants, and graphical appendices showing how parameter values vary with individual catchment descriptors, are reported in the ReFH2 technical guidance (Wallingford HydroSolutions 2015). Catchment-descriptor parameterization for this study was obtained via the FEH Web Service, using catchments that best represented the location, shape and area of the study catchments. Design storm duration is calculated from catchment-descriptor time-to-peak and catchment-average mean annual rainfall. With return period, design storm depth is also obtained via the FEH Web Service.

COMPARISON OF CALIBRATED AND CATCHMENT-DESCRIPTOR PARAMATERIZATION

Table 4 presents calibrated and catchment-descriptor parameter values. Values of T_p and C_{max} correspond to IRF = 0.2 in ROD, 0.4 in HWS and 0.8 in HWN; Figure 4 shows the variation in calibrated T_p and C_{max} for different values of IRF.

In ROD and HWS, C_{max} tends towards infinity as a greater proportion of the upstream impervious urban area becomes effective at the catchment monitoring point. The minimum percentage runoff that must occur in ReFH2 is equal to the percentage of the catchment that is urban impervious, multiplied by IRF. As the percentage runoff and flood peak magnitudes are fixed for the calibration events, C_{max} must increase with increasing IRF, to offset increased runoff from the impervious fraction with increased losses in the rural fraction. This can lead to unrealistically high values of C_{max} when $URBEXT_{2015}$ × IRF approaches the runoff percentages of calibration events (at approximately 0.4 in ROD and 0.7 in HWS).

ROD includes areas with combined surface and waste water drainage (Miller *et al.* 2014), which divert part of each storm event to a sewage treatment works, which in this case discharges downstream of the monitoring point. This diversion reduces the contribution of the urban area at the monitoring point, leading to similarity between catchment-descriptor and calibrated C_{max} only for low IRF. In HWN, calibrated values of C_{max} are lower than catchment-descriptor values for almost all IRF. As piped drainage dominates and is directed towards the monitoring point, it is reasonable to assume that most of the impervious area is contributing (although some impervious surface runoff may infiltrate in adjacent greenspace). The low values of calibrated C_{max} here limit the losses that can occur. Additionally, zero-values for BR in HWN result from non-existent baseflow, while low T_p values highlight the impact of storm drainage. Increased urbanization redirects more net rainfall to the urban unit hydrograph, which has a shorter time-to-peak, but is intended to represent a faster transfer of runoff over urban surfaces to rivers, rather than pipe flow. The calibrated T_p and C_{max} values in HWS are relatively insensitive to IRF over a wide range (from ~0.2 to ~0.5), despite the catchment being heavily urbanized, which suggests a smaller discrepancy between this catchment's dominant runoff processes and ReFH2's model structure.

Using catchment descriptors, C_{max} is highest in HWN, whereas it would be expected to be highest in ROD, where limestone is present. This is due to the imprecise delineations of the catchments using the 50-metre DEM (Table 1) and the low spatial resolution of the baseflow index catchment descriptor, which assumes even mixing of all soil types within each 1-km square. This highlights a potential benefit of consulting soil maps directly for small-catchment studies.

DISCUSSION: EVENT MODELLING

VALIDATION DATA

Sufficient flow data exist within each catchment to make reasonable gauged estimates of the median annual flood, QMED. Two common procedures for estimating QMED from these data are available, involving either consideration of annual maxima (AMAX) or peaks-over-threshold (POT) data (Langbein 1949; Bezak *et al.* 2014). QMED is estimated as the median value of an AMAX series or the weighted average of two consecutively-ranked flood peaks in a POT series, where the weighting and choice of flood peaks depends upon the record length and dispersion (temporal clustering) of the peaks (Robson & Reed 1999). As POT series contain more data, QMED estimates made using POT data benefit from smaller sampling error.

Sufficient catchment information also exists to allow use of the improved FEH statistical method (Kjeldsen *et al.* 2008) at each site. This is the most commonly-used regression-based flood estimation model in the UK and is fully independent of ReFH2. As no at-site gauged flows are used, QMED estimates from the improved FEH statistical method suffer from a larger factorial standard error than those from gauged data. The estimates can, however, provide an independent comparison with ReFH2.

Estimates of QMED are presented in Table 5, using AMAX data, POT data (with UK-average dispersion assumed), and the improved FEH statistical method with urban adjustment (Wallingford HydroSolutions 2016b) and donor transfer. QMED estimates from POT data use the entire record at each station, not just the events selected for model calibration. A gauged daily mean flow record for the Ray at Water Eaton, for the period October 1974-September 2016, was transformed according to Chen *et al.* (2017) to give an estimated daily instantaneous peak flow record. This was used to adjust the gauged QMED estimates towards estimated long-term averages, resulting in a 22.6% reduction to all values. The 95%

confidence intervals (bracketed values in Table 5) have upper bounds at 2.3 (AMAX), 2.0 (POT) or 3.4 (improved FEH statistical) times the lower bound. Table 5 shows good agreement between different estimation methods in ROD and HWS, however the improved FEH statistical estimate of QMED in HWN is vastly below the data-based estimates. This is because the monitored AMAX and POT values implicitly incorporate the dominance of the storm drain system. Although the improved FEH statistical method was calibrated to non-rural catchments, these were typically hundreds of square kilometres in area, with a mix of flow regimes, and rarely with such high urban fractions.

EVENT MODELLING

The ReFH2-modelled response of each study catchment to the design-duration 2-year storm is illustrated in Figure 5, with three different sets of estimated parameters, derived from: i) gauged data at 15-minute resolution; ii) gauged data aggregated to hourly resolution; and iii) FEH catchment descriptors (Bayliss 1999). Table 6 presents values for initial conditions C_{ini} and BF_0, both of which differ between (i), (ii) and (iii) as they depend on C_{max}. For (i) and (ii), T_p and C_{max} values as reported in Table 4 are used with the corresponding values of IRF. As-rural or “greenfield” response, using identical parameterization to (iii) but with $URBEXT_{2015}$ reduced to zero, is also shown in Figure 5. Considering the catchments as rural affects calculation of BF_0 but not C_{ini}. Horizontal lines on each plot show QMED estimated using gauged-at-site POT data and the improved FEH statistical method, while corresponding shaded areas show 95% confidence intervals of those estimates.

In ROD and HWS, the use of 15-minute calibration data results in almost the same time-series runoff hydrograph as the use of hourly calibration data. This may not be surprising as the dominant flood processes seem to happen at a rate that can be represented adequately by hourly sampling, shown by calibrated T_p values around 3-4 hours. The main implication of this is that hourly-sampled rainfall and runoff data are generally adequate for model calibration, even for heavily-urbanized catchments of only a few square kilometres. However, even in catchment HWN, in which sub-hourly processes are apparent, the timing and magnitude of the modelled peak (3.70 m^3/s @ 54 minutes vs. 3.30 m^3/s @ 66 minutes) imply that enough information is contained within the hourly-sampled data for model calibration. This study therefore provides some evidence that catchments governed by sub-hourly processes can be represented by models calibrated using hourly data in the event that higher temporal resolution data are not available.

Figure 5 shows large differences between the QMED estimates made by ReFH2 before and after calibration in each catchment. Specifically, calibration causes a reduction in estimated peak flow rate in catchments ROD and HWS, but an increase in peak flow rate in HWN. It was stated earlier that the catchment outlet of HWN is located in a storm sewer system, which is the catchment's primary drainage mechanism. This could explain why calibration reduces T_p so substantially and shows that greater density of piped drainage systems within a catchment increases the connectivity of impervious areas, increasing the fraction of effective to total impervious area. This increases the peakedness of the urban direct runoff hydrograph and increases the utility of temporally high-resolution data. Peak magnitude can be controlled by adjusting either T_p, C_{max} or IRF, as demonstrated in Figure 4. However, changes in C_{max} only affect rainfall routed via rural or permeable urban fraction of a catchment, the extent of which is increased or decreased via IRF. The effective imperviousness of HWN also explains why calibration reduces C_{max} so significantly: as the piped system allows negligible infiltration, ReFH2 is calibrated to model the (very limited) observed losses. Greater losses would be expected in summer in a natural catchment with the same climate – effectively, the piped system simulates winter, impeded-drainage soil conditions year-round and can result in the combination of an intense summer storm with "winter"-type runoff behaviour.

While storm sewers may experience dry-weather flows, the source of these flows is intrusion from outside the pipes. Hence, risk is low for new systems, increasing with age (Thorndahl *et al.* 2016). The relatively low age of the system in HWN, which is also the primary drainage mechanism, could explain why no dry-weather flows are observed. Non-zero values are estimated for the catchment-descriptor baseflow parameters in HWN, as the model structure assumes a permanent watercourse. The considerable distance between calibrated and catchment-descriptor baseflow parameters in HWN results from a mismatch between ReFH2's model structure, conceptualized around baseflow and runoff routing, and the dominant storm drainage processes.

In contrast to HWN, model calibration in HWS reduces modelled peak flow, such that it is only slightly higher than the catchment-descriptor "greenfield" runoff peak. However, these calibrated peak flow rates are only just below the upper confidence bound of QMED estimated from POT analysis. Calibration also delays modelled peak flow to the extent that the peak after calibration occurs at around the same time as the catchment-descriptor "greenfield" runoff peak. That HWS, a heavily-urbanized catchment, behaves as an apparently rural one, could be explained by the presence and location of a large contiguous green area, formed of the Seven Fields Nature Reserve, a public garden and a cemetery, occupying 15-20% of the total catchment area and bordering the main watercourse into which the catchment drains on both sides along most of its length. Hence, almost all surface runoff in HWS must flow over the green area, which is almost certainly far rougher than typical urban surfaces, resulting in a longer time-to-peak than expected for a catchment with such high URBEXT values. ReFH2's lumped structure does not discriminate between different spatial arrangements of urban areas. However, if runoff in one catchment, originating in an urban area, must flow over an adjacent rural area, then the effective contributing urban area is lower than for a catchment in which runoff from an urban area can enter a watercourse directly. Kjeldsen *et al.* (2013) found a potential positive link between T_p-ratio and the FEH descriptor URBCONC, which quantifies how many urban grid squares are adjacent to other urban grid squares. However, these results were based on 7 catchments with a typical $URBEXT_{2000}$ of 0.15 and could not be safely generalized. The advantage of high-resolution spatial data in medium-density suburban catchments is to allow more accurate quantification of the sizes and locations of green areas, and hence of the effective urban area.

In ROD, calibration of ReFH2 reduces the flood time-to-peak but also reduces the peak magnitude, resulting in a noticeable reduction of total flood volume after calibration. As in HWS and HWN, the calibrated flood peak magnitude is closer to the POT estimate of QMED than the uncalibrated flood peak magnitude. Compared to HWS and HWN, a relatively low IRF of 0.2 was chosen to model this catchment in ReFH2, despite urbanization being extremely high, even in comparison to the other two study catchments. Because of the fixed runoff fraction from impervious urban areas, each rainfall timestep has an enforced minimum percentage runoff before runoff from the rural and permeable urban areas is added. In ROD, for $IRF \geq 0.18$, at least 10.6% of event rainfall becomes runoff, more than the mean percentage runoff of the calibration events in ROD (Table 3). Considering that IRF represents the ratio of effective to total impervious area, its low value is likely to result primarily from some bypassing of the monitoring point, which also justifies the reduction in flood volume brought by calibration. While some flow is known to bypass the monitoring point, diverting to a sewage treatment works, the unavailability of information on detailed drainage connections in the upper reaches of the catchment further complicates the accurate definition of contributing area. Other factors contributing to the low IRF could include "hard" retention or detention features (e.g. permeable paving), poor condition of urban surfaces (e.g. cracks), fragmentation of impervious areas (particularly within suburban areas), and long overland flow paths (e.g. from the north-east corner of the catchment to a watercourse), It is also important to consider that different land-use datasets class urban/suburban cover differently (Branger *et al.* 2013) and interaction between artificial surfaces and drainage can result in effective impervious area varying (Han & Burian 2009).

In all three catchments, the statistical equation estimate of QMED is closer to the catchment-descriptor ReFH2 peak flow than is the gauged estimate of QMED. In this case, the closeness of the two catchment descriptor-based estimates is due to their fundamental assumptions about the catchment being modelled. Both were developed using large data sets comprised primarily of larger catchments in which natural hydrological processes dominate and localized unusual features can occupy only a small fraction of the total area. Furthermore, both rely upon the ability to define an effective contributing area. This highlights the importance of selecting the correct model structure: similarity between different model outputs can give increased confidence, but only if both model structures are appropriate. For extremely modified catchments, like HWN, no hydrological model is strictly suitable, and the similarity between the statistical equation and uncalibrated ReFH 2 estimates is irrelevant to their accuracy. Instead, a more detailed hydraulic model, considering individual (not lumped) network elements is necessary. However, distributed hydraulic model structures have their own uncertainties, in topology (e.g. presence of undocumented connections), parameterization (e.g. unknown pipe roughness) and structural assumptions (e.g. provision for leakage). This also highlights the importance of defining contributing area correctly for models that require it – it can be observed, for example, that the storm drainage area of ROD varies from 5.5-6.0 km^2 depending on the mapping method used (Table 1). Braud *et al.* (2013) identified accurate determination of catchment area as particularly important in peri-urban areas, with mixed urban-rural land use and storm drainage and sewer systems. Drainage area can be difficult to estimate accurately at small spatial scales, and depends on the resolution of the DEM used. Additionally, natural catchment area can be artificially altered via storm drainage networks (Miller *et al.* 2014), and contributing catchment area can physically alter and relative rural/urban contributions vary under antecedent conditions (Jankowfsky *et al.* 2014). ReFH2's loss model, based on an evolving relationship between rainfall and available soil moisture capacity, can model variable contributing area.

CONCLUSIONS

In this study, we conducted an applied test of ReFH2's performance in three small, heavily-urbanized catchments; further explored the procedure of how to represent urban areas within the model; and assessed the benefits of using high-resolution data for model calibration. Through this assessment, we aimed to identify advantages and shortcomings to the use of lumped, simplified model structures in catchments where detailed hydraulic modelling is commonly perceived as necessary.

For two of three study catchments, the magnitude of the modelled 2-year flood peak after calibration falls inside the confidence interval given by analysis of POT data, indicating that ReFH2 can make good estimates in certain types of small, heavily-urbanized catchment, given sufficient calibration data. The overestimation observed in one catchment could be attributable to a mismatch between the above-ground and below-ground catchment boundaries. Although this was accounted for somewhat by storm drain mapping and assuming a low fraction of contributing impervious area, the unavailability of information on detailed drainage connections in the upper reaches, in the context of the remaining overestimation, highlights that the contributing catchment area can in some cases depend more on underground topology, and that an in-depth topographic study to more accurately define which areas contribute to drainage inlets located within a topographic catchment may not always result in a better-defined contributing catchment area. This can be further complicated by drainage networks that discharge to more than one natural catchment, as the proportions of runoff transported across natural catchment boundaries, in both directions, will be time-varying.

Calibration always resulted in large changes to the flow hydrographs and, in all three cases, brought the modelled peak flow closer to that expected from analysis of gauged POT data. Use of 15-minute calibration data did not result in noticeably different runoff responses than use of 1-hour calibration data. Calibration accelerated runoff response in one catchment, dominated by piped drainage, but attenuated it in the other two, which were both drained by a mix of sewers, overland flow and watercourses. Small, heavily-urbanized catchments were under-represented during development of ReFH2's equations for parameterization in ungauged catchments. This study shows evidence that uncalibrated ReFH2 model runs potentially exaggerate the effect of urban areas on runoff response in small, heavily-urbanized catchments.

The large differences between impervious runoff fractions chosen to model each of these catchments (from 0.2 to 0.8), as well as the calibrated runoff responses and QMED estimates from gauged POT data, clearly demonstrate a great range of runoff behaviours in small, heavily-urbanized catchments. Indeed, both gauged POT analysis and calibrated model runs show that it is possible for a heavily-urbanized catchment to behave similarly to a rural one. In the specific case studied here, this is likely due to the presence of a green area bordering the catchment's watercourse along most of its length, which runoff from urban areas must pass over before entering the watercourse. Spatial arrangement of land types is generally not considered within lumped models. However, it is possible to do so in ReFH2 by reducing the IRF, effectively counting runoff that originates on impermeable surfaces, but is obliged to pass over permeable surfaces, as only partially "impermeable".

The high variability in runoff behaviour from different urban catchments highlights the advantages of detailed, high-resolution spatial data, and also potential areas for further research concerning rainfall-runoff model parameterization in small urban catchments. In particular, a mechanism for lumped models to differentiate between different spatial distributions of the same land types is required. In order to generalize this mechanism to ungauged catchments, relationships should be developed between IRF and measures of spatial distribution, such as landscape metrics or the FEH descriptors URBLOC and URBCONC.

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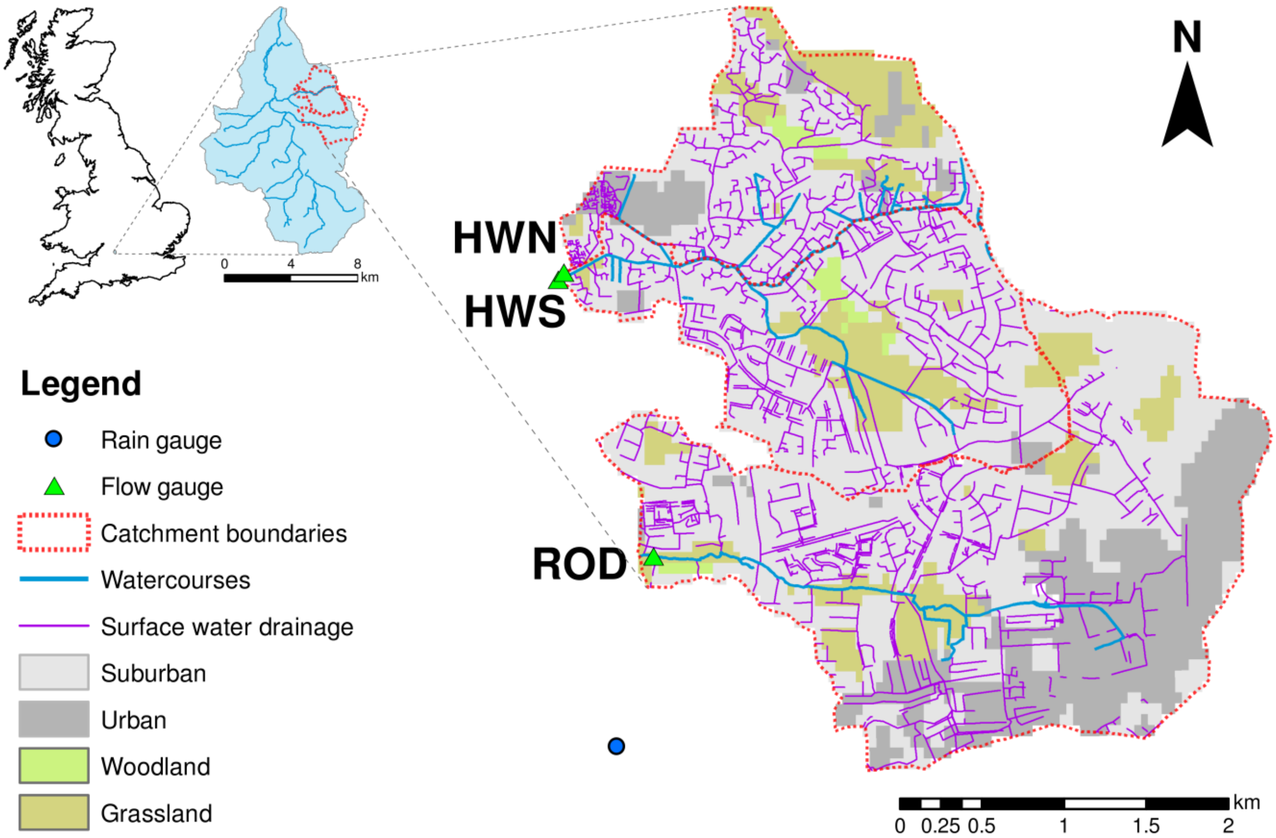

Figure 1 – Locations, land uses, watercourses and drainage networks of study catchments, with locations of flow and rainfall monitoring sites.

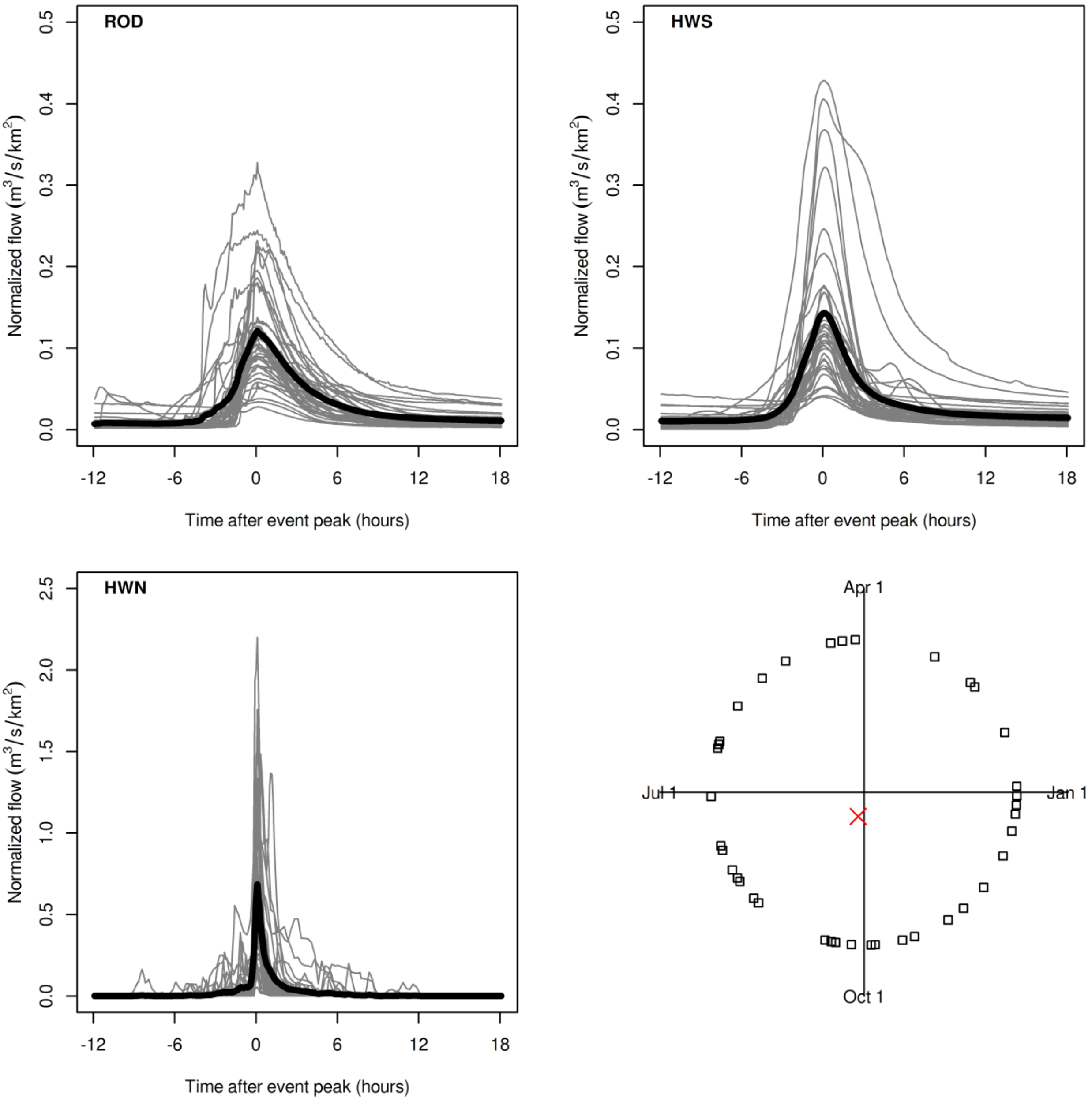

Figure 2 – Calibration event hydrographs and seasonality. Mean seasonality of all events indicated by "X".

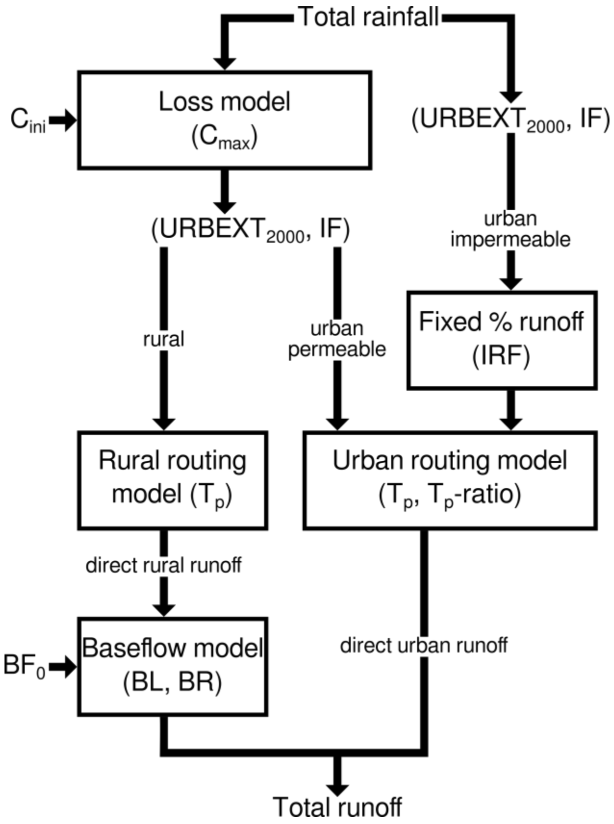

Figure 3 – ReFH2 model structure (parameters in brackets).

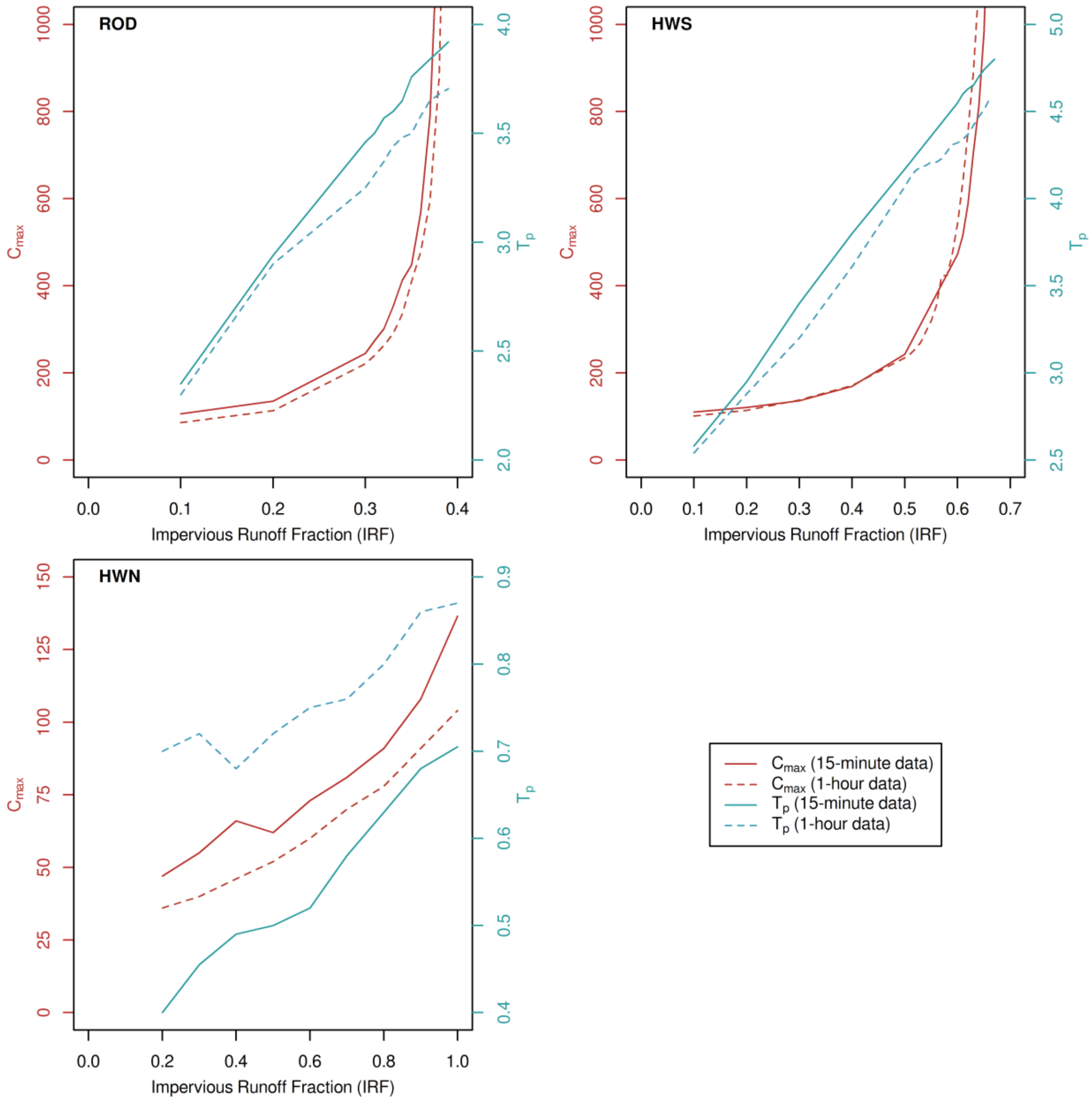

Figure 4 – Relationship between calibrated rural unit hydrograph time-to-peak (T_p), maximum soil moisture capacity (C_{max}) and runoff fraction of impervious area (IRF) for study catchments.

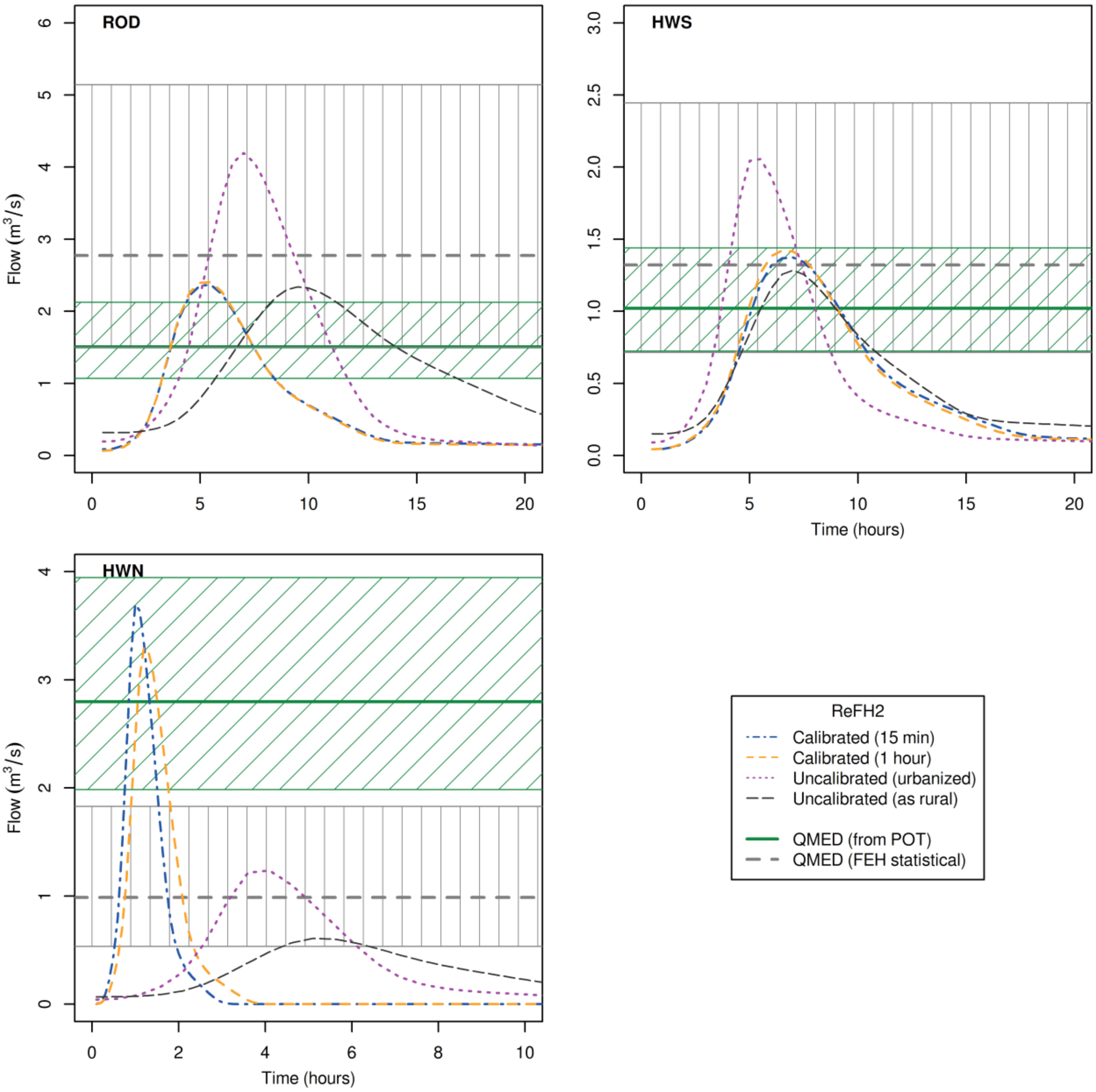

Figure 5 – Modelled catchment response to 2-year storm of design duration, using ReFH2 with parameters and initial conditions calibrated to 15-minute data (blue line), hourly data (gold line), uncalibrated (purple line) and uncalibrated greenfield (black line). Horizontal lines show estimates of QMED, shaded areas show 95% confidence intervals of these estimates. Gauged estimate from POT data shown in green, improved FEH statistical method estimate shown in grey.

Table 1 – Key characteristics of study catchments (ND – natural drainage, SD – storm drainage, DEM – digital elevation model, TOP – topographic)

Catchment name (ID)	ND area (50 m DEM) URBEXT$_{2000}$ DPSBAR BFIHOST	SD area (10 m DEM) URBEXT$_{2015}$ DPSBAR	SD area (TOP) URBEXT$_{2015}$ DPSBAR	Flow data availability	Catchment description
Haydon Wick North (HWN)	- - - -	2.18 km^2 0.46 40.6 m/km	2.12 km^2 0.45 42.0 m/km	April 2011 – October 2015	Highly urbanized, post-2000, peri-urban mixed housing and commercial development. Piped storm drainage system leading out of catchment. Mainly drains directly-connected impervious surfaces with negligible rural component.
Haydon Wick South (HWS)	6.29 km^2 0.31 33.7 m/km 0.425	3.09 km^2 0.42 33.7 m/km	3.07 km^2 0.42 27.3 m/km	April 2011 – October 2015	1950s – 2010s housing with large, contiguous are of grassland occupying 15-20% of catchment. Piped storm drainage feeding to small watercourse (Haydon Wick Brook) in catchment. Drains mix of suburban surfaces and greenspace.
Rodbourne (ROD)	5.64 km^2 0.48 14.9 m/km 0.306	5.98 km^2 0.60 14.0 m/km	5.51 km^2 0.59 14.9 m/km	May 2011 – October 2015	Highly urbanized areas of commercial and industrial development with mixed housing. Piped storm drainage feeding to small watercourse (Rodbourne stream) in catchment. Drains mix of urban, suburban and isolated greenspaces.

URBEXT$_{2000}$ – FEH catchment descriptor measuring weighted proportions of urban, suburban and inland bare ground, based on CEH Land Cover Map 2000, URBEXT$_{2015}$ – equivalent descriptor based on CEH Land Cover Map 2015, DPSBAR – mean drainage path slope, BFIHOST – baseflow index estimated from soil type

Table 2 – Rainfall statistics for 38 ReFH2 calibration events.

Statistic	Rainfall depth (mm)	Rainfall duration (hours)	Return period (years)	Peak intensity (mm/hour)
Minimum	5.11	2.25	<2	2.16
Mean	9.86	10.15	<2	6.05
Maximum	21.54	77.25	<2	19.60

Table 3 – Mean runoff statistics for 38 ReFH2 calibration events. Centroids calculated according to e.g. Dingman (1994)

Catchment	Percentage runoff	Normalized peak runoff ($m^3/s/km^2$)	Half-peak width (hours)	Time-to-peak (hours)	Peak-to-peak delay (hours)	Time-to-centroid (hours)	Centroid-to-centroid delay (hours)
ROD	10.34	0.131	5.30	5.61	2.25	8.31	4.49
HWS	8.28	0.144	4.24	6.10	2.73	8.71	4.89
HWN	9.51	0.705	0.82	3.94	0.58	4.49	0.67

Table 4 – ReFH2 model parameter values

Parameter	Data	Catchment		
		ROD	HWS	HWN
BL (hours)	15-minute	49.10	52.38	-
	1-hour	54.12	53.31	-
	Catchment-descriptor	30.57	31.83	36.53
BR (-)	15-minute	0.80	1.08	0
	1-hour	0.86	1.03	0
	Catchment-descriptor	0.71	0.87	1.23
T_p (hours)	15-minute	2.94	3.80	0.63
	1-hour	2.90	3.61	0.80
	Catchment-descriptor	4.73	3.27	2.54
C_{max} (mm)	15-minute	135	169	91
	1-hour	113	171	78
	Catchment-descriptor	249	291	408

Table 5 – Gauged and statistical estimates of the median annual flood peak (m^3/s) at each study site. Bracketed values indicate 95% confidence intervals.

	ROD	HWS	HWN
QMED (AMAX)	1.71 (1.13-2.58)	1.01 (0.67-1.53)	2.69 (1.78-4.06)
QMED (POT)	1.51 (1.07-2.12)	1.02 (0.72-1.44)	2.80 (1.98-3.94)
QMED (statistical)	2.78 (1.50-5.14)	1.30 (0.70-2.40)	0.97 (0.52-1.79)

Table 6 – ReFH2 initial conditions for design event modelling

Initial condition	Data	Catchment		
		ROD	HWS	HWN
C_{ini} (mm)	15-minute	67.98	62.77	17.63
	1-hour	56.90	63.52	15.11
	Catchment-descriptor	125.6	108.2	79.13
	Catchment-descriptor (greenfield)	152.6	137.8	110.6
BF_0 (m^3/s)	15-minute	0.086	0.042	0.000
	1-hour	0.064	0.043	0.000
	Catchment-descriptor	0.193	0.090	0.042
	Catchment-descriptor (greenfield)	0.320	0.150	0.068