Rainfall–streamflow relationships for three chalk escarpment springs (Oxfordshire, United Kingdom): effective rainfall and groundwater recharge area computational issues

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ABSTRACT

Flow responses to rainfall are investigated for three small chalk springs located within about 30 km of each other. A high degree of synchronicity is shown for the spring hydrographs, which exhibit a lag of about 50 days relative to a much larger local reference catchment. Rainfall–streamflow models with six or fewer parameters, calibrated using free-to-download software, account for about 75% of the variance in daily streamflow for the reference catchment, and between about 76 and 85% for the chalk springs. Several modelling issues are discussed related to computation of the daily effective rainfall that forms the input to a Unit Hydrograph part of the model. Descriptions are given of how and why, when the recharge area used for a spring is far too small, the modelling software generates physically unrealistic effective rainfall depths much greater than the rainfall, without affecting model-fit to streamflow or the calibrated values of model parameters (except one). Reasons are suggested why it can be pragmatically acceptable for computed effective rainfall to occasionally exceed the corresponding recorded rainfall by small amounts. Wider implications of the modelling results are outlined and some suggestions for further work are made.

Key words | chalk, groundwater, unit hydrographs, modelling, springs, streamflow

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HIGHLIGHTS

- Rainfall–streamflow models for 3 chalk springs (similar research unknown).
- Insights to the computation of effective rainfall.
- Novel application of Unit Hydrograph based rainfall–streamflow modelling.
- Insights gained on calibrated model parameters.
- Discussion includes consideration of alternative loss models and effects of raingauge under-catch on rainfall–streamflow modelling.

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INTRODUCTION

About one third of the public water supply for England and Wales is from groundwater (Price 1996), with about 55% from chalk aquifers (Lloyd 1993). From west to east, the Lambourne, Chilton, Blewbury, Ewelme and Swyncombe Downs form a distinctive chalk landscape in south Oxfordshire, UK. Employing the IHACRES hybrid conceptual-metric rainfall–streamflow modelling approach (Jakeman *et al.* 1990; Littlewood & Jakeman 1994), the paper investigates three groundwater streams that start at the base of the approximately north-facing escarpment of the Downs; Letcombe Brook at Letcombe Bassett, Mill Brook at Blewbury and Ewelme Brook at Ewelme. IHACRES has been applied to model streamflow in the UK (e.g. Sefton & Howarth 1998) and elsewhere (e.g. Post & Jakeman 1996, 1999) but as far as is known this paper is the first time it has been used to model spring flows from an aquifer.

Streamflows for the brooks are measured at flat-V weirs located short distances downstream of a pool (or pools) where groundwater emerges as springs. There are no mapped surface stream networks above the springs. Flows at the gauging sites are almost entirely groundwater from the chalk. To provide a regional hydrology context and introduce the modelling methodology applied to the brooks, flows are also modelled for the Pang at Pangbourne, which is on the dip-slope of the chalk and has a large groundwater component at its Crump weir gauging site (though not as large as at the gauging stations for the brooks). The maximum distance between any of the four flow gauging sites is about 29 km. Each brook flows towards the middle reaches of the Thames: after flowing for about 15 km, Letcombe Brook joins Childrey Brook, a tributary of the Ock which is gauged at Abingdon just before it joins the Thames; Mill Brook flows for about 10 km, becoming Bradford's Brook about 2 km before it joins the Thames at Wallingford; and Ewelme Brook flows for about 4 km before reaching the Thames at Benson.

Objectives of the paper are to (a) check the catchment/recharge areas published for the three brooks (suggesting better values in two cases) and (b) investigate the effects on IHACRES model parameters and estimated effective rainfall when inaccurate catchment/recharge areas are used for model calibration. A subsidiary feature of the paper is that it uses only readily available, public-domain hydroclimatic data and its associated metadata, e.g. hydrometric data from the UK National River Flow Archive (NRFA 2020). Apart from readily available rainfall, streamflow and air temperature time series, and catchment area, the modelling approach employed uses no other catchment data or information.

The paper has four further sections. Comparisons of the brooks are presented in the first section, looking at their hydrometric data in different ways and using the Pang at Pangbourne as a reference catchment. The second section describes the main features of the IHACRES rainfall–streamflow model and the associated modelling methodology applied in this paper. The third section starts by modelling the rainfall–streamflow dynamics of the Pang at Pangbourne, to demonstrate the modelling methodology which is then applied to the brooks. Discussion and concluding remarks comprise the fourth section.

COMPARING THE BROOKS

Table 1 includes selected published details of the four catchments referred to in this paper, and their specific mean flows (flow per km^2) calculated using the published areas. The following simple analysis of hydrometric data, particularly for

Table 1 | Catchment details

Catchment	Area (km^2) NRFA	Area (km^2) (1)	Mean flow (m^3/s)	Specific mean flow^a (m^3/s/km^2)	Catchment rainfall (mm/year)	BFI (2)
Letcombe Brook	4.0	23	0.09	0.023	733	0.96
Mill Brook	2.0	30	0.11	0.055	651	0.96
Ewelme Brook	13.4	–	0.05	0.0037	696	0.97
Pang	170.9	–	0.65	0.0038	694	0.87

Sources: Unless stated otherwise, CEH (2003) and NRFA (2020).

[a] Using area from the second column.

(1) Recharge area estimated in this paper (more than two significant figures are not justifiable).

(2) Base Flow Index (Gustard *et al.* 1992).

streamflow because it is a synthesis of catchment processes and is well measured (whereas there are issues with rainfall measurement and the estimation of catchment rainfall – see later), shows that the NRFA areas for Letcombe Bassett and Blewbury given in Table 1 are too small to sustain the measured flows of the springs (NRFA metadata warns of this). Table 1 shows that the mean specific flow above Letcombe Bassett (0.023 $m^3/s/km^2$) is only about half that above Mill Brook at Blewbury (0.055 $m^3/s/km^2$), though rainfall is 13% higher. The nominally much larger area of Ewelme Brook to Ewelme, where average annual rainfall is between that for Letcombe Bassett and Blewbury, has a much lower mean specific streamflow (0.0037 $m^3/s/km^2$). The Pang at Pangbourne has a mean specific flow of 0.0038 $m^3/s/km^2$, about the same as that for Ewelme Brook to Ewelme, which supports the interdependent notions that (a) for an annual rainfall of about 695 mm, specific streamflow from the local chalk, including along the escarpment, is fairly uniform at about 0.0038 $m^3/s/km^2$ and (b) 13.4 km^2 for Ewelme Brook at Ewelme is a reasonable estimate of its groundwater recharge area. For Mill Brook at Blewbury, using a specific streamflow of 0.0038 $m^3/s/km^2$ gives a recharge area of about 29 km^2. For Letcombe Brook at Letcombe Bassett, the similarly estimated recharge area is about 24 km^2. These estimates were adjusted slightly for lower or higher annual catchment rainfall than about 695 mm. For analyses presented in subsequent sections, Table 1 records that 30 and 23 km^2 have been used for the recharge areas to Blewbury (rainfall 651 mm/year) and Letcombe Bassett (733 mm/year), and 13.4 km^2 has been used for Ewelme Brook.

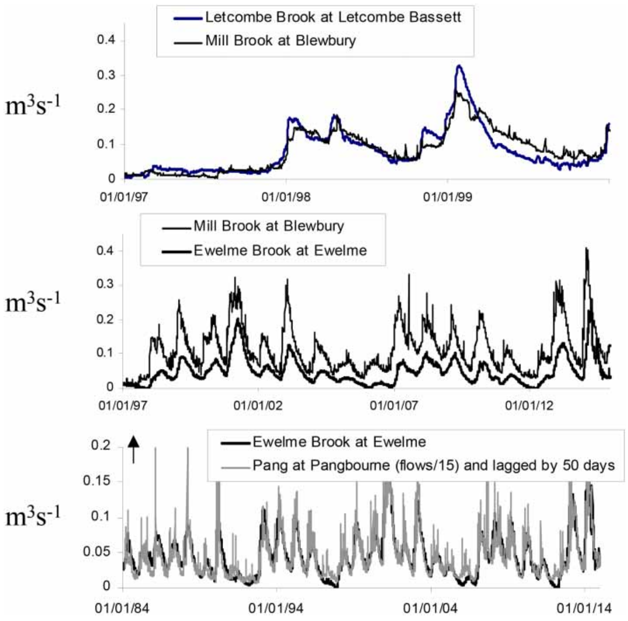

Figure 1 | Hydrographs for Mill Brook, Ewelme Brook and Letcombe Brook.

As expected, hydrographs for the brooks are strongly seasonal and exhibit a high degree of synchronicity, as shown in Figure 1 (upper panels). There is an indication in the top panel that Letcombe Brook recesses more quickly than Mill Brook. The lowest panel in Figure 1 shows hydrographs for Ewelme Brook and the Pang at Pangbourne, where the latter has been scaled downwards by a factor of 15 and delayed by 50 days (both factors were chosen by manual trial and error to obtain a reasonable match). Apart from when flows at Pangbourne are high, or when flows at Ewelme are very low, the Pangbourne (transformed) and Ewelme hydrographs follow each other closely. The brooks at their gauging sites, and the Pang at Pangbourne, are strongly influenced by slow-response groundwater flow from the chalk but the Pang is also affected by a quicker, non-groundwater contribution to streamflow, as reflected in its lower baseflow index, BFI, of 0.87 (CEH 2003; NRFA 2020; see Gustard *et al.* (1992) for the BFI method) compared with BFIs of 0.96 or 0.97 for the brooks (Table 1).

The flows of a wide range of UK rivers and streams tend to approach a log-normal distribution as the length of record analysed increases. The Pang at Pangbourne flow-duration curve (FDC), 1969–2017, shown in Figure 2 illustrates this well, even though low flows of the Pang at Pangbourne

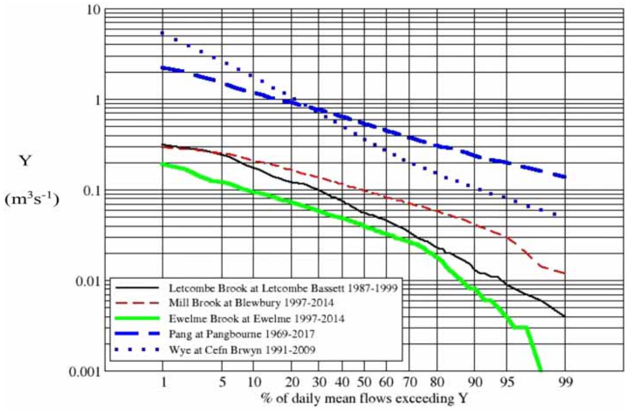

Figure 2 | Flow-duration curves.

can be affected by abstractions from the chalk. The steeper the slope of a log-normal FDC, the larger the variance in streamflow. The FDC for the Wye at Cefn Brwyn (mid-Wales) is shown in Figure 2 to provide a contrast with the chalk streams. FDCs for the three brooks exhibit convex-upwards shapes to varying degrees, though the FDC for Ewelme Brook between 1 percentile and 70 percentile flows follows a log-normal distribution quite closely. The markedly convex-upwards portion of the Ewelme Brook FDC is distinctive. Low flows at Ewelme can decrease rapidly after summer and autumn periods of little or no rainfall (zero flows are sometimes recorded). Low flows at Blewbury and Letcombe Bassett are better sustained than at Ewelme.

THE MODEL AND MODELLING METHODOLOGY

Jakeman *et al.* (1990) introduced the IHACRES model and its associated modelling methodology. The version of the model used here is described by Jakeman & Hornberger (1993) and was first made widely available in the PC-IHACRES software package (Littlewood *et al.* 1997). IHACRES has been mostly applied to catchments that have a mapped network of streams and where flow at the basin outlet is not predominantly groundwater (unlike the brooks). The software used here is version v2.1.9 described by Croke *et al.* (2006b). Detailed accounts of IHACRES are given elsewhere (e.g. Jakeman *et al.* 1990; Littlewood 2008, 2009), so only features of the model and modelling methodology pertinent to later sections of the paper will be given here.

The specific model structure employed has two conceptual modules in series; a non-linear loss module followed by a linear Unit Hydrograph (UH) module. The loss module converts a time series of rainfall, r_k, at time-step k, to effective rainfall, u_k, and has three calibrated dynamic response characteristics (DRCs): an exponential decay time constant, τ_w (units [T]), which defines the rate at which a catchment wetness index, s_k [–], decreases in the absence of rainfall; a parameter f [$^\circ\mathrm{C}^{-1}$] that modulates τ_w according to air temperature, t_k [°C]; and a factor c [L^{-1}] that assumes the same volumes of computed effective rainfall and recorded streamflow over the model calibration period. Equations (1)–(3), from Jakeman & Hornberger (1993), define how the loss module works. An optimal value for c is found by a trial-and-error routine within the IHACRES software. Optimal values of τ_w and f are found by a software-assisted manual search of the $\tau_w - f$ parameter space for a best overall model-fit to recorded streamflow.

$$s_k = c\,r_k + (1 - \tau_w^{-1})\,s_{k-1} \tag{1a}$$

$$= c\,(r_k + (1 - \tau_w^{-1})\,r_{k-1} + (1 - \tau_w^{-1})^2 r_{k-2} + \ \ldots) \tag{1b}$$

$$u_k = r_k s_k \tag{2}$$

$$\tau_w(t_k) = \tau_w \exp\left((20 - t_k) f\right) \tag{3}$$

Values of $1/c$ [L] are presented and discussed in later sections since $1/c$ can be considered to be indicative of the depth of a conceptual catchment wetness store. Equation (1a) shows how s_k is computed recursively and Equation (1b) shows the classic antecedent precipitation index nature of s_k. Equation (3) includes a reference temperature of 20 °C. It can be noted that although s_k should always be less than 1 it is not constrained to be so within the software, resulting in the possibility that computed effective rainfall can be greater than rainfall. This facet of the loss module and its effects on model-fit and the values of calibrated model parameters are illustrated and further discussed later.

The linear UH module converts u_k to modelled streamflow, x_k. The time series analysis technique for calibrating the UH module parameters is described by Jakeman *et al.* (1990) (and references therein) and lies outside the scope of this paper. The module allows the prescription of a configuration of linear UH stores; for this paper, it is restricted to either a single store or two stores acting in parallel. When the configuration is two stores in parallel, one represents a dominant quick-flow response ($x^{(q)}{}_k$) and the other a dominant slow-flow response ($x^{(s)}{}_k$); $x_k = x^{(q)}{}_k + x^{(s)}{}_k$. With this configuration, the UH module has three calibrated DRCs: exponential decay time constants for quick- and slow-flow UHs, $\tau^{(q)}$ and $\tau^{(s)}$ [T]; and a slow-flow index $0 < \mathrm{SFI} < 1$ [–]. The SFI is the volume of modelled slow-flow as a proportion of the volume of modelled streamflow over the calibration period and is analogous to BFI. Adopting the notation used in v2.1.9 of the IHACRES software

(Croke *et al.* 2006b), when a single-UH-store module is prescribed its decay time constant is τ_1 and the peak of the UH is β_0 [L^3/T], with $\beta_0 = 1 - \exp(-1/\tau_1)$ to comply with the conservation of mass. The whole model applied here has a maximum of just six calibrated DRCs and is, therefore, a gross simplification of hydrological processes.

MODELLING RESULTS

Missing daily streamflow measurements for Mill Brook for December 2001 cover a period of low rainfall and were estimated by linear interpolation (it is considered unlikely that this has a noticeable effect on the low flow end of the FDC in Figure 2 which includes periods of very low Mill Brook flows, e.g. 2004–2006 and 2011–2013 as illustrated in Figure 4). At the time of writing, this gave availability of complete calendar years of daily rainfall and streamflow from 1997 to 2014 for both Mill Brook (after infilling) and Ewelme Brook. For Letcombe Brook, daily rainfall and streamflow records were available for complete calendar years from 1987 to 1999. To provide context for subsequent modelling of the brooks, the modelling starts with the Pang at Pangbourne.

The Pang at Pangbourne

Summaries of models calibrated for the Pang at Pangbourne are given in the first four rows of Table 2, where terms not already introduced are: $-\infty < D < 1$ is a coefficient of determination ($D < 0$ indicates that a model-fit is worse than using the mean flow at all times and $0 < D < 1$ is the proportion of the initial variance in streamflow accounted for by a model); and ARPE is an average relative parameter error for the calibrated UH module parameters. Equations for D and ARPE are given in Jakeman *et al.* (1990). The effects on model-fit of using different air temperature datasets were assessed using models with a single-UH-store module. Model P1 did not use any air temperature data, whereas models P2 and P3 used Benson temperatures (Met Office 2020) and Oxford temperatures (Burt & Burt 2019), respectively. Each day in a given month was assigned the nominal temperature for that month. The benefit of using temperature data, i.e. the cyclical Benson monthly mean temperature data (the same 12 values repeated each year), is shown in Table 2 as an increase in D from 0.578 (P1) to 0.677 (P2). Replacing Benson temperatures (which do not capture interannual variations) with Oxford temperatures (a separate value for each month throughout the record) increased D further, to 0.701 (P3). Although Benson is closer than Oxford to the Pang catchment (about 16 and 32 km from Pangbourne, respectively), the Oxford temperature record contains more information and gives the better model-fit. The Oxford temperature record was therefore used for subsequent modelling of the Pang and, later, the brooks.

Although model P3 gives a fairly good fit to recorded flows, a better model, P4, accounting for about 75% of the variance in streamflow, was obtained by prescribing two UH stores in parallel. Figure 3 shows the simulation P4 model-fit and its residuals, from 1969 to 2017. Model P4

Table 2 | Model results

Model	D	ARPE	τ_w (days)	f (°C^{-1})	$1/c$ (mm)	τ_1 (days)	β_0 (m^{3}s^{-1})	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	SFI
P1	0.578	<0.0005	61	0.0	750	59.2	0.017	–	–	–
P2	0.677	<0.0005	11.1	1.8	514	55.8	0.018	–	–	–
P3	0.701	<0.0005	8.3	2.1	437	58.6	0.017	–	–	–
P4	0.749	0.003	5.1	2.6	383	–	–	6.84	97.8	0.78
M1	0.849	<0.0005	1.7	3.3	255	112	0.009	–	–	–
M2	0.844	1.127	2.0	3.5	318	–	–	1.22	112	0.99
E1	0.798	<0.0005	2.4	5.8	822	118	0.008	–	–	–
L1	0.759	<0.0005	1.7	4.9	673	50.2	0.020	–	–	–

Models: Pang at Pangbourne (P); Millbrook at Blewbury (M); Ewelme Brook at Ewelme (E); Letcombe Brook at Letcombe Bassett (L).

Calibration periods: models P1–P4, 22 September 1997 to 30 December 2017; models M1 & M2, 28 October 1997–25 February 2012; model E1, 27 October 1997–26 February 2012; model L1, 12 October 1989–19 January 1997.

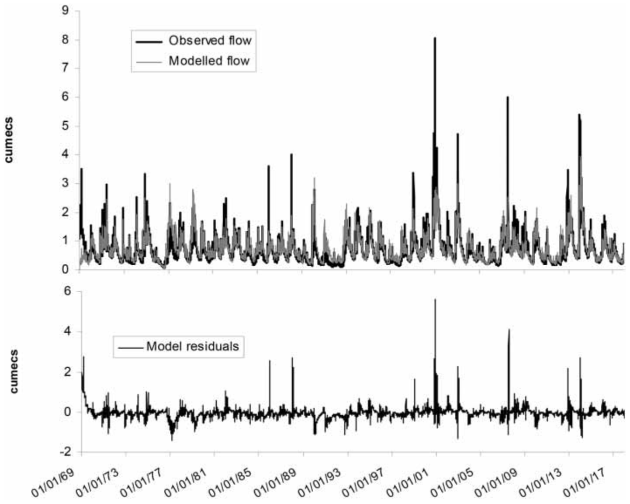

Figure 3 | Pang at Pangbourne model P4 in simulation mode 1969–2017.

gives slightly better tracking of recessions than single-UH-store model P3. Furthermore, model P4 allows continuous separation of modelled streamflow into dominant quick- and slow-response hydrographs. The Pang at Pangbourne SFI (model P4) is 0.78 and its BFI (NRFA) is 0.87. SFI is arguably the superior of these analogous indices: whereas BFI is determined solely from information in streamflow time series data and uses simple geometric rules for hydrograph separation to give fairly arbitrary baseflow and direct flow components (Gustard *et al.* 1992), SFI is an output of IHACRES modelling using information in rainfall, streamflow and air temperature time series to give dominant quick- and slow-flow components of streamflow that have UH definitions. All four models, P1–P4, generate $s_k < 0.6$ (and therefore compute $u_k < r_k$) over the entire modelled period. The DRCs in Table 2 are for a single calibration period and should, if only for that reason, be interpreted with caution. However, it can be noted that model P4 values for $\tau^{(q)}$ and $\tau^{(s)}$, of 6.84 days and 97.8 days, respectively, lie reasonably on either side of 58.6 days for τ_1 from model P3.

The brooks

The models calibrated for the brooks are given in Table 2 beneath the results for the Pang. Mill Brook model M1, Ewelme Brook model E1 and Letcombe Brook model L1 account for about 85, 80 and 76% of the streamflow variances (D), respectively. Each model has a single-UH-store module. Simulation-mode model fits over the periods of record available are shown in Figures 4 and 5. A two-UH-stores-in-parallel model calibrated for Mill Brook (model M2) gave a slightly lower value of D (0.84) and a much

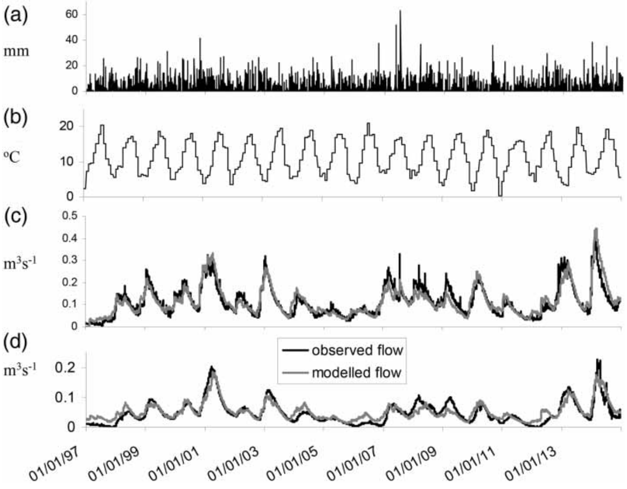

Figure 4 | Rainfall, air temperature and streamflow 1997–2014; (a) Mill Brook daily rainfall, (b) Oxford monthly air temperature, (c) Mill Brook observed and M1-modelled daily streamflow and (d) Ewelme Brook observed and E1-modelled daily streamflow.

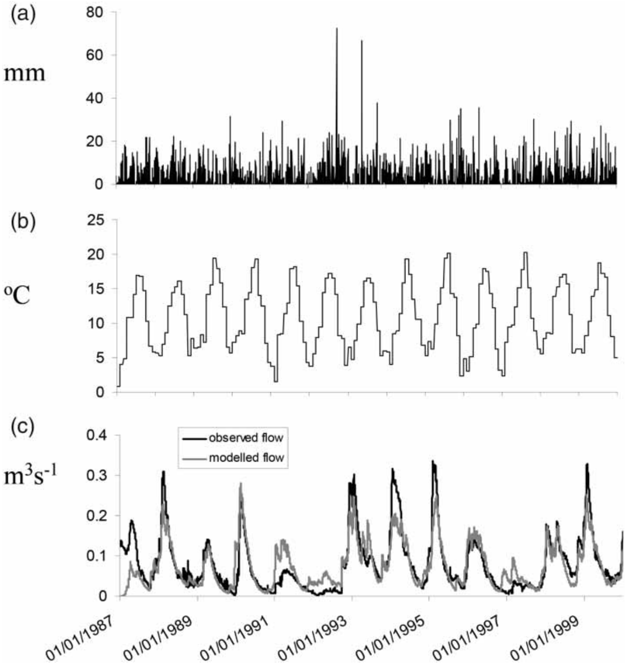

Figure 5 | Rainfall, air temperature and streamflow 1987–1999; (a) Letcombe Brook daily rainfall, (b) Oxford monthly air temperature and (c) Letcombe Brook observed and L1-modelled daily streamflow.

higher ARPE (1.127) than model M1 indicating a relatively high degree of uncertainty associated with the UH parameters. However, it can be noted that model M2 has an SFI of 0.99 (cf. BFI 0.96), consistent with the flow of Mill Brook at Blewbury being continuously almost all groundwater. Also worth noting is that τ_1 in model M1 and $\tau^{(s)}$ in model M2 are both 112 days, indicating further that the additional relatively quick-flow component of model M2 ($\tau^{(q)} = 1.22$ days) is not beneficial. In general when applying IHACRES with two UH stores in parallel, if the contribution to the streamflow by either quick or slow flow is very small relative to the other, it can be difficult to identify the smaller flow component with good precision. This can be indicated by high values of ARPE (as for model M2) or the UH model parameters may even fail to converge when attempting to calibrate a two-UH-stores-in-parallel model (as happened for Ewelme and Letcombe Brooks). The single-UH-store models M1, E1 and L1 have the merit of having the same simple model structure to assist comparisons.

As for Pang model P4, the DRC values for models M1, E1 and L1 in Table 2 should be interpreted with caution. The quality of models for the brooks and the Pang, in terms of D, should be kept in mind; the lower the D the less confidence should be placed on DRC values. The results indicate that compared with the Pang, the brooks have lower values of τ_w and higher values of f. The values for f of 5.8 and 4.9 $^\circ\mathrm{C}^{-1}$ for Ewelme Brook and Letcombe Brook, respectively, are the highest this author has seen for UK catchments. For comparison, values of f for seven catchments in Wales (Littlewood 2003) are between 1.1 and 2.4 $^\circ\mathrm{C}^{-1}$ whereas for the Pang (P4, Table 2), f is 2.6 $^\circ\mathrm{C}^{-1}$. The relatively high values of f for the brooks are consistent with the rapid drying of surface and near-surface layers commonly observed in the catchments of these small headwater chalk streams. The much shorter UH decay time constant, τ_1, for Letcombe Brook of about 50 days compared with the other brooks (112 and 118 days) supports the earlier observation from Figure 1 that flows at Letcombe Bassett decrease more quickly than at Blewbury.

Concerning the loss module

Loss module DRC c assumes that the volume of effective rainfall 'is equal to the total streamflow volume over the calibration period, after adjustment for change in catchment storage between the beginning and end of the period … It is not really a free parameter but a normalizing one' (Jakeman & Hornberger 1993). Ideally, therefore, calibration periods should be selected to start and end at the same low flow at the end of very long recessions, when catchment storages of water can be assumed to be the same. In practice, however, such long recessions do not often (if ever) present themselves in UK streamflow records. In which case there could be substantially different storages of water in the catchment at the start and end of pragmatically selected calibration periods. The effect of this is also likely to be different for different catchments. These sources of uncertainty in computed values of c should be recognized when comparing the values of $1/c$ (Table 2) of 255, 822 and 673 mm for Mill Brook, Ewelme Brook and Letcombe Brook, respectively; from the limited analysis presented here, there is no obvious pattern to the relative magnitudes of $1/c$ for the brooks.

A potentially confusing aspect of parameter c comes to the fore when applying IHACRES software to Mill Brook and Letcombe Brook, as follows. The software adjusts c by trial and error such that the volumes of effective rainfall and streamflow over a pragmatically selected model calibration period are nearly the same. The value of c returned by the software depends on the area (km^2) employed to compute the volume of effective rainfall. For example, when a Mill Brook model is calibrated over the same period used to calibrate model M1 (recharge area 30 km^2), but this time employing an area of 2 km^2, the value for $1/c$ of 17 mm is 15 times smaller than for model M1 (255 mm). When this model calibrated using 2 km^2 is applied in simulation mode from 1997 to 2014 most daily values of computed s_k greatly exceed 1 (maximum s_k about 8.5) and the depth of computed effective rainfall over the modelled period is a totally unrealistic 258% of the rainfall. However, calibrated values of the DRCs other than c remain the same whatever recharge area is used for Mill Brook because, as can be seen from Equation (1b), c is simply a scaling factor on an antecedent precipitation index. This applies generally: for a given catchment and calibration period, the temporal pattern of s_k has the same (scaled) shape whatever area is used. Therefore, basically, the same information is passed from the loss module to the UH module, leading to the same calibrated values for the DRCs (except c). So, when Equations (1)–(3) give $s_\mathrm{k} \gg 1$

and massively over-estimate u_k over a calibration period, it is likely to be because the area used is far too small, i.e. it is highly inaccurate. The analyst simply has to replace the inaccurate recharge (or catchment) area with a more accurate one and re-run the model calibration. Where possible, the specific discharge used for calculating a recharge area should be based on local aquifer properties rather than, as in this paper, a value for the local region derived solely from hydrometric data from nearby catchments. The remainder of this section describes circumstances when occasional $s_k > 1$, by small amounts, can be acceptable.

When, as above, an area of 2 km^2 is used for Mill Brook a relatively small component of the severe over-estimation of u_k could be due to under-estimation of r_k or over-estimation of streamflow (or both). Consider catchment rainfall measurement (streamflow output is arguably better measured than catchment rainfall input). Under-estimation of rainfall reaching the ground, by a conventional raingauge with its aperture above local ground level (0.305 m is common in the UK), is a well-known phenomenon (e.g. Muchan & Dixon 2019). The amount of under-catch is related to wind speed across the top of the raingauge and is, therefore, variable between raingauges and rainfall events. Conventional raingauges can under-catch rainfall by about 5% in lowland areas of the UK and by 25% or more in moorland and mountainous areas (Strangeways *et al.* 2015). However, raingauge under-catch is rarely even mentioned in rainfall–streamflow modelling exercises. There is also the issue of estimating the areal rainfall input to a catchment or recharge area from point rainfall measurements but this will not be discussed further here. Even when surface topography and geology allow a catchment area to be estimated accurately, experience has shown that in some cases u_k generated by a good set of loss module DRCs occasionally exceeds the recorded rainfall, r_k, by small amounts. Such instances of $u_k > r_k$ can be considered acceptable on the basis of the uncertainty in estimates of catchment rainfall reaching the ground.

DISCUSSION AND CONCLUDING REMARKS

Modelling the three brooks has exposed aspects of the loss module given by Equations (1)–(3) that previously have not been sufficiently recognized in the literature. For example, if a catchment (or recharge) area used is X% too small then the value of $1/c$ computed by the IHACRES software will also be X% too small. Selection of non-ideal start and end times of calibration periods is an additional cause of uncertainty in c. Initially counter-intuitive, perhaps, i.e. without considering in detail how Equations (1)–(3) are implemented in the software, the values of the other calibrated DRCs (apart from c) are independent of the catchment or recharge area used. Operationally, if simple pre-modelling analysis of hydrometric data does not reveal when a very inaccurate area has been assigned to a catchment (for whatever reason), sequences of $s_k \gg 1$ ($u_k \gg r_k$) generated by IHACRES software can be an excellent indication of that error.

Loss modules other than Equations (1)–(3) have been applied within an IHACRES framework (e.g. Littlewood & Post 1993, 1995; Chen *et al.* 1995; Robinson & Stam 1993; Ye *et al.* 1997). Croke & Jakeman (2004) introduced a catchment moisture deficit (CMD) loss module for IHACRES that, like Equations (1)–(3), also has just three calibrated parameters. Equations (1)–(3) and the CMD loss module were applied to seven basins in Wales with catchment areas of between 129 and 1,480 km^2, and mean annual rainfalls between 828 and 2,189 mm (Croke & Littlewood 2005). For the two largest catchments, the CMD loss module gave a better overall model-fit than Equations (1)–(3), while for the other five catchments, it did not perform as well.

A distinguishing feature of the three brooks investigated for this paper is that their BFIs are close to 1. Gauged streamflows for other small chalk catchments in the UK comprise similarly very high proportions of groundwater (CEH 2003) but many larger chalk streams, like the Pang at Pangbourne, exhibit a more mixed-flow response where IHACRES can often identify separate dominant quick and slow flow components. A systematic IHACRES analysis of a range of UK chalk streams could contribute to better relationships between model parameters and physical catchment attributes, i.e. statistical DRC-PCD links. Such an investigation, enhanced with applications of other relevant techniques, e.g. cross correlation and Fourier analysis (Croke *et al.* 2006a), could also help to assess alternative loss modules within an IHACRES framework.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (URLs are given in appropriate references).

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