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Unit Hydrographs and United Kingdom hydrology 1990-2020: IHACRES rainfall – streamflow modelling

by

Ian G. Littlewood

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Ian G. Littlewood PhD, BSc, FCIWEM, C.WEM

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Contents

1. Introduction 1
2. IHACRES 1990 4
3. Environmental hydrology and IHACRES 15
    IHACRES applied to different types of catchment 15
    The hydrograph separation controversy 18
    Rainfall–streamflow model parameter regionalisation 19
    Extending streamflow records 21
    Model complexity issues 22
    Multi-objective model-fitting 24
    Data timestep issues 27
    Environmental change 29
        Land-use change and other interventions 29
        Climate change 29
    Streamflow forecasting 30
    Chalk stream and other groundwater-dominated flow regimes 32
    Loss modules for IHACRES 35
4. Engineering hydrology and IHACRES 37
5. IHACRES software 42
6. Concluding remarks 45
    Acknowledgements 48
    Glossary 49
    References 50

Abstract

A history is given of the application of two types of Unit Hydrograph (UH) for UK hydrology, from 1990 to 2020. The Paper outlines the UH-based rainfall–streamflow modelling methodology known as IHACRES, which was introduced in 1990, then summarises and discusses its contributions to several types of environmental hydrology study, including: hydrograph separation; analysis of droughts; rainfall–streamflow model regionalisation; extending streamflow records, investigating data timestep issues; quantifying the effects on streamflow of environmental change (land-use, climate); and characterising Chalk stream flow regimes. Advantages are discussed and illustrated of the IHACRES UH, which is for total streamflow, over the UH introduced in 1975 and still being used for UK engineering hydrology in 2021, which is for a poorly defined (unmeasurable) direct flow component of streamflow. The Paper argues that inertia to substantial change continues to effectively prevent UK engineering hydrology practice from progressing beyond using a UH for direct flow, although a demonstrably superior type of UH (for total streamflow) exists. This inertia appears to have influenced reviews of standard procedures for UK design flood hydrograph estimation, e.g. for reservoir dam spillway safety assessments, which do not mention the advances that have been made in UH identification and application over the past 30 years or so. A short Section gives an overview of three generations of free-to-use IHACRES software. The final Section of concluding remarks includes a suggestion that a range of modelling approaches for flood hydrograph estimation (including elements of the IHACRES approach) should be evaluated comparatively towards improving UK engineering flood hydrology.

Keywords: IHACRES, Unit Hydrographs, rainfall–streamflow modelling, design hydrograph estimation, reservoir spillway flood hydrology.

1. Introduction

In 2016, Members of the British Hydrological Society (BHS[1]) were invited to individually rank their top 5 items from an un-ranked list of 30 suggested key developments in hydrology and water resources management to the year 2000 (BHS, 2016a,b). Administrative events in the 30 items listed were UK-related, while landmark research publications in the list were more international. The top 10 items chosen by BHS Members collectively are ranked in Table 1, with the author's top 5 in the last column.

Table 1: BHS Survey 2016

Rank	Event or publication	Author's top five
1	Formation of the Institute of Hydrology (1968)	5
2	Flood Studies Report (1975)	3
3	Penman-Monteith evaporation equation (1965)	
4	Water Resources Act (1963)	4
5	Darcy equation for flow of water in aquifers (1856)	
6	Hortonian concept of runoff generation	
7	National River Flow Archive (1982) and predecessors	
8	Foundation of the British Hydrological Society (1983)	
= 9 & 10	The Unit Hydrograph (Sherman, 1932) and Dooge (1959)	1 and 2 respectively

Meaningful interpretation of the rankings in Table 1 is difficult, if only because the items are of widely different types. Nevertheless, the survey results provide a useful starting point for this Paper. Half of the items are focused on administrative events and half on scientific/technical aspects of hydrology; floods (rank 2), evaporation (3), flow in aquifers (5), runoff generation (6) and the Unit Hydrograph (UH) (= 9 and 10). As shown, the author's personal rankings put the UH top, while acknowledging the significance (especially for UK hydrology) of the Flood Studies Report (FSR) (NERC, 1975). These two items are of course related: when a design flood hydrograph is required for a UK catchment, whether gauged or ungauged for streamflow, procedures given by the FSR are founded largely on a UH-based rainfall–streamflow model. From 1975 to date, improvements have been made to several parts of the FSR design hydrograph procedure but its UH component has remained largely unchanged.

[1] There is a Glossary of acronyms, etc, at the end of the Paper.

Presentation of UH theory (e.g. Dooge, 1959, 1973), and procedures for its application in systematic UK flood hydrology (e.g. NERC, 1975; IH, 1999), invoke an imagined, unmeasurable, component of streamflow known as direct flow. A direct flow hydrograph over a flood event is estimated by subtracting from streamflow an imagined, unmeasurable, baseflow hydrograph (the flow estimated to have occurred in the absence of storm rainfall). An unmeasurable effective rainfall hyetograph, equal in volume to the direct flow over the period in question, is estimated by reducing the ordinates of the rainfall hyetograph to account for losses to storage and by evapotranspiration; zero exchanges of groundwater with adjacent catchments are assumed. A UH is then estimated from the effective rainfall and direct flow. Although this approach is somewhat desperate (identifying a UH from system input and output that are both umeasurable) it has played a key role in systematic engineering hydrology in the UK for at least the past 45 years.

Writing some 48 years ago, Dooge (1973, p91) mentions a

> "ground water unit hydrograph, a concept which has been studiously ignored by applied hydrologists over the past 35 years".

It is likely, therefore, that in 1973 Professor Dooge[2] (and probably others) knew that UH theory was not restricted to characterising only a direct flow (quick response) component of streamflow. It is also likely that if a technique for identifying UHs for more than one component of streamflow in a single operation had been available in the 1960s and early 1970s, then Dooge (and others) would have used it. However, the leap forward to being able to apply UH theory to simultaneously estimate separate UHs for dominant quick- and slow-response components of total streamflow did not happen until IHACRES[3] in 1990 (Jakeman, Littlewood and Whitehead, 1990).

IHACRES is a product of collaborative research between hydrologists from the Australian National University, Canberra and the (then) Institute of Hydrology, Wallingford, UK (which later became the UK Centre for Ecology and Hydrology). The first and third authors of the 1990 paper had worked previously (with others) on the time series modelling approach employed by IHACRES. Antecedents of IHACRES include work by Young (1974), Whitehead (1979) and Whitehead *et al*. (1979).

As discussed in more detail later in this Paper, the success of the IHACRES methodology is due largely to a time series systems identification technique introduced by Jakeman (1979), Young and Jakeman (1979, 1980), and Jakeman and Young (1979). IHACRES does not change UH theory but it does extend its range of application beyond flood hydrology because, with just six parameters, an IHACRES model can often characterise a large part of the whole flow regime, e.g. from 1 percentile to 99 percentile flows. With IHACRES, the only remaining unmeasurable variable involved in UH identification is the effective rainfall. Another feature of IHACRES is that hydrograph separation is an integral part of the modelling and not, as with traditional methods (e.g. NERC, 1975), a prerequisite to identification of a UH.

There is some overlap between this Paper and previous overviews of IHACRES (Littlewood and Jakeman, 1994; Littlewood, 2002a, 2008) but a substantial amount of new material and discussion has been added. The Paper is concerned mainly with IHACRES

[2] Professor Dooge became an Honorary Member of BHS in 1996.

[3] Identification of unit Hydrographs And Component flows from Rainfall, Evapotranspiration and Streamflow data.

applications to UK catchments and discussion of its potential utility for UK engineering hydrology; it does not attempt to summarise the considerable body of IHACRES-related research and its applications elsewhere, e.g. Australia. However, selected applications of IHACRES to catchments in other countries are mentioned, illustrating the utility of the methodology for catchment hydrology across a wide range of hydroclimatological settings. An additional objective of the Paper is to collate and discuss published applications of IHACRES for environmental hydrology, providing a history that will hopefully assist with further work. Although some important modelling issues are outlined, a comprehensive approach covering all modelling issues related to IHACRES has not been attempted. A final objective of the Paper is to consider the potential of IHACRES for engineering hydrology applications, e.g. design flood hydrograph estimation to assist with reservoir spillway flood hydrology.

There are five further sections to the Paper. Section 2 summarises the first IHACRES publication, by Jakeman, Littlewood and Whitehead (1990). Section 3 gives summaries, with discussion, of published applications of IHACRES, in broadly chronological order within each of several themes (see Contents page). Section 4 discusses application of UHs for engineering hydrology, comparing the UH employed currently for UK flood hydrology with the potential offered by the IHACRES UH. Section 5 covers IHACRES software packages. Concluding remarks are given in Section 6.

2. IHACRES 1990

This Section is essentially a summary of the paper by Jakeman, Littlewood and Whitehead (1990)[4], which first introduced IHACRES and gave examples of its application. Material from post-1990 IHACRES publications is included when useful as background for later parts of the Paper. Some of the notation employed differs from JLW (1990), using instead notation adopted by the same authors in post-1990 IHACRES papers. The summary presented here is not a substitute for reading JLW (1990) and citations therein, which is essential for a better understanding of certain aspects of IHACRES, e.g. the fine detail of its computational algorithms.

The overall structure of the IHACRES rainfall–streamflow model is two modules in series; a non-linear loss module to convert rainfall to modelled effective rainfall, followed by a linear UH module to convert the effective rainfall to modelled streamflow. The IHACRES model given by Eqs. 1 to 3a[5] is applied by JLW (1990) to two small, grass moorland catchments in Wales; the 0.72 km^2 Nant y Gronwen and the 0.34 km^2 Nant y Coileth, both of which had been instrumented (along with several other small basins) for the 1980s Llyn Brianne Acid Waters Project (Edwards *et al*., 1990).

JLW (1990) refer to s_k in Eqs. 1 and 2 as soil moisture content at timestep k but since the model does not attempt to account for that level of physical detail it is usually thought of as a dimensionless catchment wetness index, $0 < s_k < 1$. Also in Eqs. 1 and 2: τ is a factor (units of time, [T]) to be calibrated and is a measure of catchment memory for recent rainfall (the larger the value of τ the longer the effect of antecedent rainfall on s_k); r_k is rainfall [L]; u_k is effective rainfall [L]; and *const.* is a factor to equate the volumes of effective rainfall and observed streamflow over the model calibration period (it can also accommodate any factor needed to convert rainfall units to flow units [L^3T^{-1}]).

To allow for seasonal variation in evapotranspiration, JLW (1990) include an initial step whereby r_k in Eqs. 1 and 2 is replaced by r_k^* given by Eq. 4, where t_k is air temperature and t_m is a reference temperature such that $t_m - t_k > 0$ over the calibration period. This step was not applied by JLW (1990) for the Nant y Gronwen or the Nant y Coileth because seasonal variation in evapotranspiration could be considered negligible over the short model calibration periods used (see later).

Eq. 3a represents just one of many configurations of conceptual storages that can be prescribed for the UH module of IHACRES; in this case two first-order linear storages acting in parallel, as represented by Eq. 3b where the q and s superscripts indicate relatively quick and slow response components of streamflow, x_k. This configuration has been shown to be

[4] Shortened to JLW (1990) for this Paper.

[5] JLW (1990) present the IHACRES UH module in terms of discrete-time transfer functions, like Eqn. 3a. For corresponding continuous-time transfer functions see, for example, Young (2011).

more effective than other configurations for a wide range of catchment types around the world, and is therefore a focus in this Paper.

$$s_k = s_{k-1} + \tau^{-1}(r_k - s_{k-1}) \quad \text{Eq. (1)}$$

$$u_k = const.\, r_k s_k \quad \text{Eq. (2)}$$

$$x_k = \left(\frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}} \right) u_{k-\delta} \quad \text{Eq. (3a)}$$

$$= \left[\left(\frac{\beta^{(q)}}{1 + \alpha^{(q)} z^{-1}} \right) + \left(\frac{\beta^{(s)}}{1 + \alpha^{(s)} z^{-1}} \right) \right] u_{k-\delta} \quad \text{Eq. (3b)}$$

$$r_k^* = t_m^{-1} (t_m - t_k)\, r_k \quad \text{Eq. (4)}$$

In Eq. 3a, the UH part of the model: x_k is modelled streamflow [L or L^3T^{-1}]; b_0, b_1, a_1 and a_2 are transfer function parameters identified by IHACRES using the Simple Refined Instrumental Variable (SRIV) method (Jakeman, 1979; Young and Jakeman, 1979, 1980; and Jakeman and Young, 1979); z^{-n} is the backward shift operator such that $z^{-n}u_k = u_{k-n}$; and δ is an optional pure time delay [T].

The general form of Eq. 3a is given by Eq. 5, where m and n are the largest orders of z^{-1} in the denominator and numerator respectively. The pair (m, n) refers to different numbers and configurations of first-order (1, 0) stores in the UH module. Thus Eq. 3a represents a (2, 1) configuration, i.e. two first-order (1, 0) stores acting in parallel. Other configurations are described later. The (m, n) notation is employed frequently in this section and later parts of the Paper.

$$x_k = \left(\frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ \ldots\ + b_n z^{-n}}{1 + a_1 z^{-1} + a_2 z^{-2} + \ \ldots\ + a_m z^{-m}} \right) u_{k-\delta} \quad \text{Eq. 5}$$

Eq. 3b is the decomposition of Eq. 3a to two (1, 0) transfer functions acting in parallel, one representing dominant quick flow (q) and one dominant slow flow (q), where $-1 < \alpha^{(.)} < 0$). The α and β parameters can be calculated from the a and b parameters by multiplying out the two first-order components of Eq. 3b, then equating coefficients of z^{-n} with those in Eq. 3a, to give equations Eqs. 6 to 9. A quadratic equation in $\alpha^{(q)}$ or $\alpha^{(s)}$ can be derived from a combination of Eqs. 8 and 9 and then solved by the appropriate standard formula. Calculation of the other α parameter, and the β parameters, then follows.

$$b_0 = \beta^{(q)} + \beta^{(s)} \qquad \text{Eq. 6}$$

$$b_1 = \beta^{(q)}\alpha^{(s)} + \beta^{(s)}\alpha^{(q)} \qquad \text{Eq. 7}$$

$$a_1 = \alpha^{(q)} + \alpha^{(s)} \qquad \text{Eq. 8}$$

$$a_2 = \alpha^{(q)}\alpha^{(s)} \qquad \text{Eq. 9}$$

Eqs. 10 to 13 in Table 2 present equations given by JLW (1990) for quick and slow flow characteristics, in terms of the α and β parameters for a (2, 1) model. In post-1990 IHACRES publications these characteristics ($\tau^{(q)}$, $\tau^{(s)}$, $v^{(q)}$ and $v^{(s)}$) are referred to as dynamic response characteristics (DRCs).

Table 2: IHACRES DRCs for a (2, 1) structure

DRC	Quick flow	Slow flow
UH exponential decay response times [T]	$\tau^{(q)} = \frac{-\Delta}{\ln(-\alpha^{(q)})}$ Eq. 10	$\tau^{(s)} = \frac{-\Delta}{\ln(-\alpha^{(s)})}$ Eq. 11
Relative volumetric throughput [-]	$v^{(q)} = \left(\frac{\beta^{(q)}}{1+\alpha^{(q)}}\right)\left(\frac{1}{V}\right)$ Eq. 12	$v^{(s)} = \left(\frac{\beta^{(s)}}{1+\alpha^{(s)}}\right)\left(\frac{1}{V}\right)$ Eq. 13

where $V = \frac{\beta^{(q)}}{1+\alpha^{(q)}} + \frac{\beta^{(s)}}{1+\alpha^{(s)}}$

and Δ is the data timestep, e.g. 1 hr

Using a (2, 1) model structure for Nant y Gronwen and Nant y Coileth, JLW (1990) describe how an optimal value of τ (Eq. 1) is found initially by a trade-off of two model-fit statistics. The trade-off is between a high value for a coefficient of determination, D, given by Eq. 14[6] and a low average relative parameter error (ARPE) for the *a* and *b* UH module parameters, given by Eq. 15. In Eq. 14 y_k is observed streamflow and *N* is the number of timesteps in the calibration period. ARPE is calculated from standard errors of the *a* and *b* parameters, which are by-products of the SRIV algorithm. In Eq. 15**,** σ denotes standard deviation and ^ denotes an estimate. The trade-off is necessary because maximum D and minimum ARPE do not typically occur at a single value of τ but separately at values of τ not far apart (see JLW (1990) for further details). A trade-off between D and ARPE does not guarantee a best model for all purposes but it has been found to work well in many cases. Additional model-fit criteria may be applied (an example, using flow duration curves, is given in Section 3 'Multi-objective model-fitting').

$$D = 1 - \frac{\sum_{k=1}^{k=N} \left(y_k - x_k\right)^2}{\sum_{k=1}^{k=N} \left(y_k - \bar{y}\right)^2} \qquad \text{Eq. 14}$$

$$ARPE = \left[\left(\frac{\hat{\sigma}_{a_1}}{\hat{a}_1} \right)^2 + \left(\frac{\hat{\sigma}_{a_2}}{\hat{a}_2} \right)^2 + \left(\frac{\hat{\sigma}_{b_0}}{\hat{b}_0} \right)^2 + \left(\frac{\hat{\sigma}_{b_1}}{\hat{b}_1} \right)^2 \right] / 4 \qquad \text{Eq. 15}$$

A (2, 1) model structure described by Eqs. 1 to 3a for the Nant y Gronwen, calibrated by JLW (1990) using hourly rainfall and streamflow over a period of 400 hours in September 1987, has values of D and %ARPE of 0.95 and 0.021 respectively. The identical model structure calibrated for the Nant y Coileth over 600 hours, also in September 1987, gives values of D and %ARPE of 0.85 and 0.041. Suspected poorer quality of streamflow data for the Nant y Coileth may partly explain its lower D and higher %ARPE.

Outputs from the PC-IHACRES software package (Littlewood *et al*., 1997) will now be used to help summarise and discuss the JLW (1990) results for the Nant y Gronwen. (PC-IHACRES and two other IHACRES software packages are discussed in Section 5.) In the PC-IHACRES package the loss module given by Eqs. 16 to 18 (Jakeman and Hornberger, 1993)[7] is used instead of the JLW (1990) loss module given by Eqs. 1, 2 and 4. In Eqs. 17 and 18, $\tau_w(t_k)$ is a temperature-modulated catchment drying rate τ_w [T], where τ_w and f [$^oC^{-1}$] are parameters to be calibrated, and R is a reference temperature. As mentioned earlier, temperature data were not used by JLW (1990) to modulate τ_w over short periods of record for the Nant y Gronwen; in practice a dummy time series for temperature can be input to PC-IHACRES and *f* in Eq. 18 set to zero, effectively replacing $\tau_w(t_k)$ in Eq. 17 by τ_w.

[6] JLW (1990) used the notation R^2 instead of D but D was used in subsequent IHACRES papers and has been used here.

[7] Shortened to JH (1993) for this Paper when discussing loss modules.

$$u_k = r_k s_k \qquad \text{Eq. 16}$$

$$s_k = cr_k + \left(1 - \frac{1}{\tau_w(t_k)}\right) s_{k-1} \qquad \text{Eq. 17a}$$

$$= c\left(r_k + \left(1 - \tau_w(t_k)^{-1}\right) r_{k-1} + \left(1 - \tau_w(t_k)^{-1}\right)^2 {r_{k-2}}^2 + \ldots\right) \qquad \text{Eq. 17b}$$

$$\tau_w(t_k) = \tau_w e^{(0.062 f (R - t_k))} \qquad \text{Eq. 18}$$

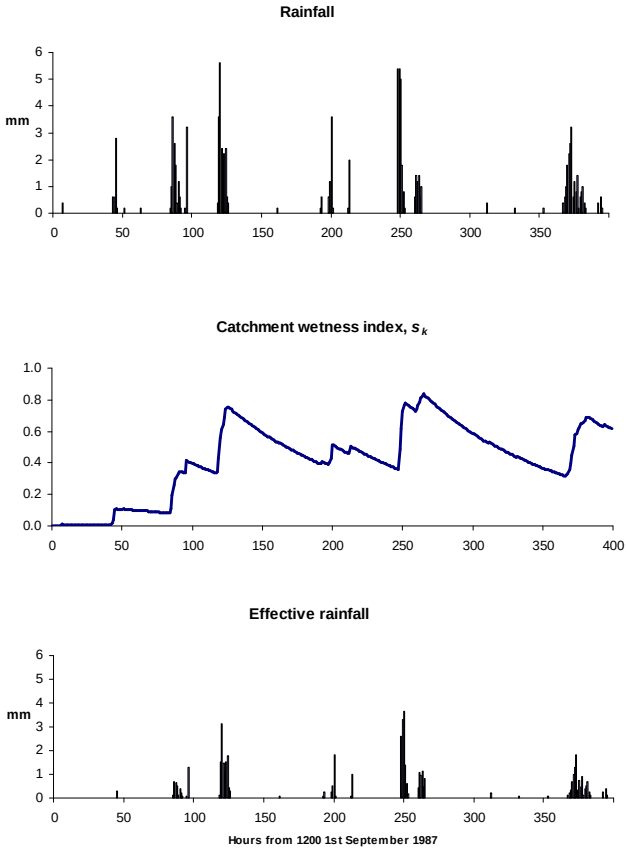


Figure 1: Nant y Gronwen rainfall, catchment wetness and effective rainfall

For the (2, 1) Nant y Gronwen model, Fig. 1 shows the effect of the catchment wetness index, s_k, operating on the rainfall, r_k, to generate effective rainfall, u_k. The wetness index, s_k, initialised at zero, quickly reaches an operating level about which it varies in a reasonable manner, increasing rapidly with rainfall and decreasing more slowly during periods of catchment drying between rainfall events. Fig. 2 shows the PC-IHACRES model-fit to streamflow, the UHs and the hydrograph separation. Figures 1 and 2 will be referred to again later.

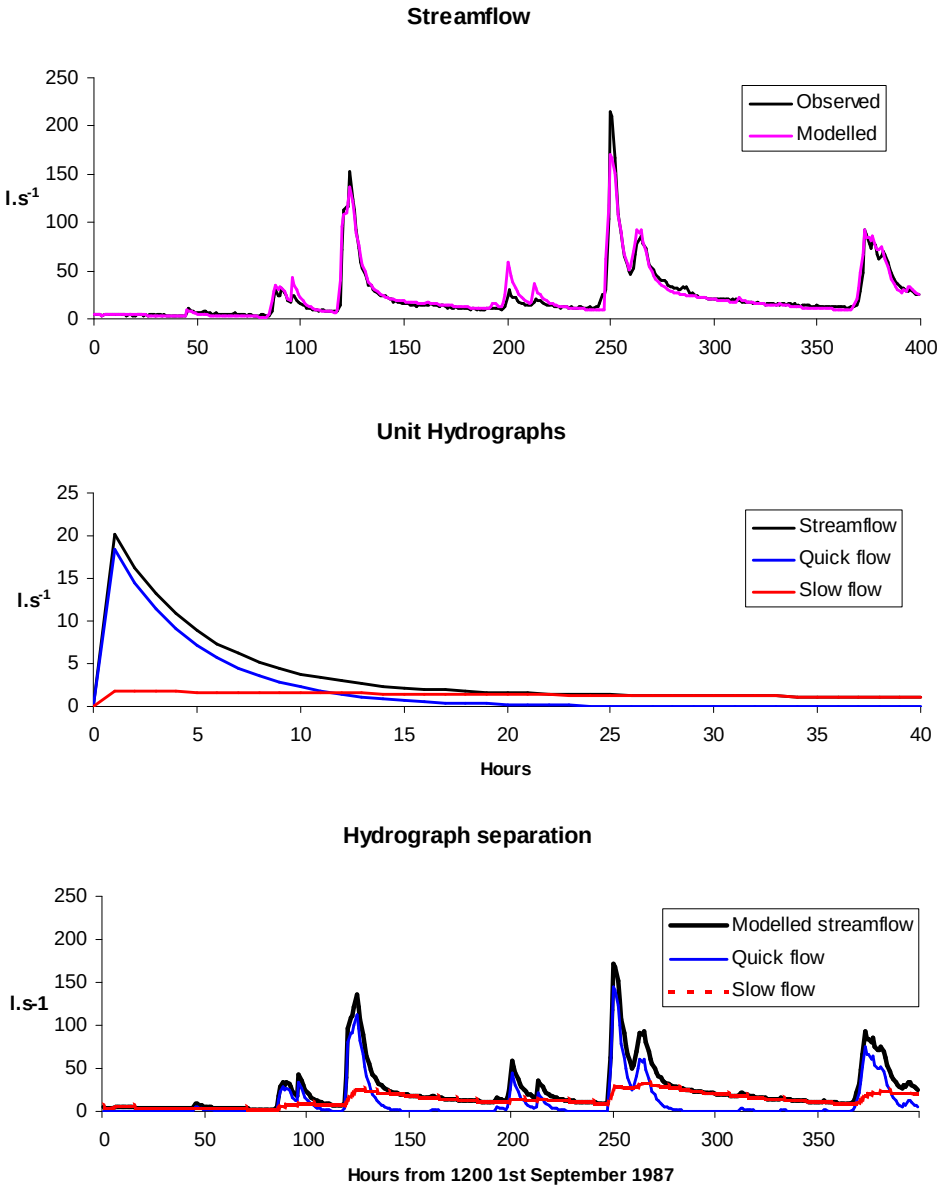


Figure 2: Nant y Gronwen model-fit, unit hydrographs and hydrograph separation

Calibrated values of the Nant y Gronwen *a* and *b* parameters (Eq. 3a) are given in Table 3. The top rows show the JLW (1990) estimates with their standard errors in parentheses. The bottom row shows corresponding estimates calibrated using the JH (1993)

loss module, which agree well with those in the top row using the JLW (1990) loss module. PC-IHACRES returns confidence limits on the computed DRCs instead of standard errors on the *a* and *b* parameters. Table 4 gives the asymmetric 68% confidence limits on the DRCs derived by PC-IHACRES from the (symmetric) standard errors on the *a* and *b* parameters. The standard errors in Table 3 and the confidence intervals in Table 4 are pleasingly small.

Table 3: Nant y Gronwen *a* and *b* transfer function parameters

Loss module	a_1	a_2	b_0	b_1
JLW (1990)	-1.7836 (± 0.0070)	0.7859 (± 0.0068)	20.4317 (± 0.4056)	-19.9046 (± 0.3840)
JH (1993)	-1.7790	0.7818	20.0995	-19.4836

Table 4: Nant y Gronwen UH DRCs

Loss module	DRC		
	$\tau^{(q)}$ (hours)	$\tau^{(s)}$ (hours)	$v^{(s)}$ (-)
JLW (1990) *	4.40	90.1	0.61
PC-IHACRES**	4.30 (4.13, 4.44)	74.3 (68.7, 80.6)	0.60 (0.59, 0.61)

Calibration period: 400 hours from 1200 hrs 1st September 1987

* JLW (1990) loss module parameter τ = 86 hours

** JH (1993) loss module parameter τ_w = 100 hours

Table 4 shows that the estimated values of $\tau^{(q)}$ (and $v^{(s)}$) are similar when either loss module is used. The difference between the $\tau^{(q)}$ using the two loss modules is only about 2% and the difference between the $v^{(s)}$ is also about 2%. The most notable difference is a shorter $\tau^{(s)}$ when the JH (1993) loss module is used (by about 17%). Comparison of the top panel of Fig. 2 with Fig. 3 of JLW (1990) (not reproduced here) reveals almost imperceptible differences in the modelled hydrographs using either loss module. Both loss modules give a value for D of 0.95. The JLW (1990) and JH (1993) loss modules give %ARPE values of 0.0214 and 0.0315 respectively.

Modelled streamflow, x_k, in the top and bottom panels of Fig. 2, can be calculated by recursive application of Eq. 19, which is derived by rearranging Eq. 3a (with δ = 0, for simplicity of presentation) and applying the backward shift operator. Modelled quick and slow flow hydrographs in the bottom panel of Fig. 2, $x_k^{(q)}$ and $x_k^{(s)}$, are given by Eqs. 20 and 21. The UH for total streamflow shown in the middle panel of Fig. 2 is given by applying Eq. 19 with u_k = 1 at k = 1 and u_k = 0 for all other k. The quick and slow flow UHs are given by similar application of Eqs. 20 and 21 respectively.

$$x_k = b_0 u_k + b_1 u_{k-1} - a_1 x_{k-1} - a_2 x_{k-2} \qquad \text{Eq. (19)}$$

$$x_k^{(q)} = \beta^{(q)} u_k - \alpha^{(q)} x_{k-1}^{(q)} \qquad \text{Eq. (20)}$$

$$x_k^{(s)} = \beta^{(s)} u_k - \alpha^{(s)} x_{k-1}^{(s)} \qquad \text{Eq. (21)}$$

Consider now the optimal configuration of (1, 0) storages in the UH module. Table 5 lists values of D and %ARPE obtained by JLW (1990) for different prescribed configurations of (1, 0) storages for the two catchments they studied. For the Nant y Coileth, a (1, 0) UH module gives a slightly lower (better) %ARPE than a (2, 1) module, the latter configuration giving the highest D for any tried for that catchment. For the Nant y Gronwen, which has the better-quality flow data, a (2, 1) module gives a higher D and lower %ARPE than for the Nant y Coileth. Subject to good-quality data at an adequately small data timestep (to capture the quick flow dynamics), the two (1, 0) stores acting in parallel configuration, i.e. a (2, 1) module, which is optimal for the Nant y Coileth and the Nant y Gronwen, has been found to be optimal for a wide range of catchments (see later).

Table 5: Model-fit D and %ARPE for different configurations of UH storages

Configuration of first-order (1, 0) UH storages	(*m*, *n*)	Nant y Gronwen		Nant y Coileth	
		D	%ARPE	D	%ARPE
One	(1, 0)	0.819	0.032	0.731	0.036
Two in series	(2, 0)	0.821	21.3	0.734	23.3
Two in parallel	(2, 1)	0.945	0.021	0.852	0.041
Three in series	(3, 0)	0.845	0.364	0.754	1.11
Two in series with a third in parallel (to the two in series)	(3, 1)	0.901	0.822	0.788	2.16
Three in parallel	(3, 2)	0.908	38.1	unstable model	

Data from Jakeman, Littlewood and Whitehead (1990)

As Table 5 shows, JLW (1990) report a three-stores-in-parallel (3, 2) UH module for the Nant y Gronwen, of the form given by Eqs. 22a and 22b. Although the (3, 2) model fits the data nearly as well as the (2, 1) model (D 0.908 and 0.945 respectively), its %ARPE is 38.1 compared with 0.021 for the (2, 1) model. The much higher %ARPE indicates that increasing the complexity of the UH module structure is accompanied by higher standard errors, on average, on the UH transfer function *a* and *b* parameters. If, for example, an *a* parameter is not significantly different from zero, it is not justifiable statistically in the model. Jakeman and Hornberger (1993) illustrate this aspect of IHACRES modelling for several other catchments, and discuss its implications for choosing appropriate levels of complexity

in rainfall–streamflow models generally when they are calibrated using only hydroclimatic time series data (see 'Model complexity issues' in Section 3).

$$x_k = \left(\frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}} \right) u_k \qquad \text{Eq. (22a)}$$

$$= \left[\left(\frac{\beta_1}{1 + \alpha_1 z^{-1}} \right) + \left(\frac{\beta_2}{1 + \alpha_2 z^{-1}} \right) + \left(\frac{\beta_3}{1 + \alpha_3 z^{-1}} \right) \right] u_k \qquad \text{Eq. (22b)}$$

The computational algorithm employed to estimate the *a* and *b* parameters is of crucial importance. Table 6 gives model-fit statistics from JLW (1990) for the Nant y Gronwen for least squares (LS), basic (BIV) and Simple Refined (SRIV) Instrumental Variable methods – see JLW (1990) and Young (2011) for detailed information about IV methods. As JLW (1990) say,

> "These results from both the LS and BIV algorithms wrongly suggest that there is only one identifiable [UH] component … The fit obtained by least squares estimation was very similar, both BIV and LS estimation techniques performing reasonably well in matching peaks of the streamflow hydrograph but seriously underestimating the recessions".

The SRIV algorithm used in IHACRES overcomes this problem, as illustrated earlier in Fig. 2.

Table 6: Nant y Gronwen *a* and *b* parameters estimated by LS, BIV and SRIV

method	a_1	a_2	b_0	b_1	%ARPE	D
LS	-0.8804 (± 0.1982)	0.0424 (± 0.1709)	15.3466 (± 1.780)	6.9673 (± 4.321)	14.6	0.792
BIV	-0.7733 (± 0.2364)	-0.0381 (± 0.2032)	15.2651 (± 0.1.606)	8.7720 (± 5.028)	723	0.795
SRIV*	-1.7836 (± 0.0070)	0.7859 (± 0.0068)	20.4317 (± 0.4056)	-19.9046 (± 0.3840)	0.0214	0.945

Data from JLW (1990)

* These results are given in **Tables 2 and 3** but again here for ease of comparison with LS and BIV

There was some early resistance to IHACRES. Littlewood and Jakeman (1994) briefly allude to this difficulty but the story is worth telling in some detail because it reinforces the message delivered by Table 6.

After presenting early IHACRES results to colleagues within the Institute of Hydrology (IH)[8], (e.g. Littlewood and Jakeman, 1991a), the author learned that a colleague believed that IHACRES was being over-sold because, in their view, it was impossible to identify solely from the input and output of a two-component mixed-exponential system the parameters of those two components. That IHACRES could 'do the impossible' was demonstrated as follows.

A time series agreed as being representative of effective rainfall (u_k^*) was passed through a (2, 1) transfer function that was the addition of two (1, 0) transfer functions, the chosen parameters of which were not known to the author. It was requested that the two (1, 0) transfer functions had a reasonable difference between their decay time constants. Thus a time series of fake streamflow (q_k^*) was generated, which was passed to the author. Using only the SRIV algorithm in PC-IHACRES with inputs of u_k^* and q_k^*, the author estimated the *a* and *b* parameters of the chosen (1, 0) transfer functions with a precision of better than one part in a million, thus demonstrating the ability of IHACRES to identify the separate parameters of a two-component mixed-exponential decay system.

A possible reason why the efficacy of IHACRES was challenged as outlined is that it was doing something that had not been done previously in rainfall–streamflow modelling. Advantages of IV methods, particularly the SRIV method, were not widely known amongst hydrologists in the early 1990s. As can be seen from Table 6, if LS and BIV methods are applied within an IHACRES framework it does, indeed, appear to be 'impossible' to resolve a mixed exponential response to give two separate dominant components of streamflow – but the SRIV method solves this problem. The JLW (1990) paper explains and demonstrates this advantage of the SRIV algorithm quite clearly but the exercise that has been described here serves to reinforce the point.

Two graphics summarise the inputs to and outputs from IHACRES. Fig. 3 shows the IHACRES model structure and the six DRCs corresponding to a (2, 1) model that includes the JH (1993) loss module. Figure 4 shows the UHs, and the time series inputs and outputs, for the Teifi at Glan Teifi modelled with a daily data timestep (monthly temperatures were assigned to each day of a month). The slow flow UH for the Teifi at Glan Teifi is relatively small and therefore difficult to see in Fig. 3. The slow flow hydrograph separation can be seen more clearly.

As indicated in Fig. 3, the DRC of proportional volumetric contribution of slow flow to streamflow, $v^{(s)}$ (see Eq. 13), is a Slow Flow Index ($0 < SFI < 1$) analogous to the Base Flow Index (BFI) that has been used extensively for UK hydrology (e.g. Gustard *et al*., 1992; IH, 1999).

[8] Now the UK Centre for Ecology and Hydrology.

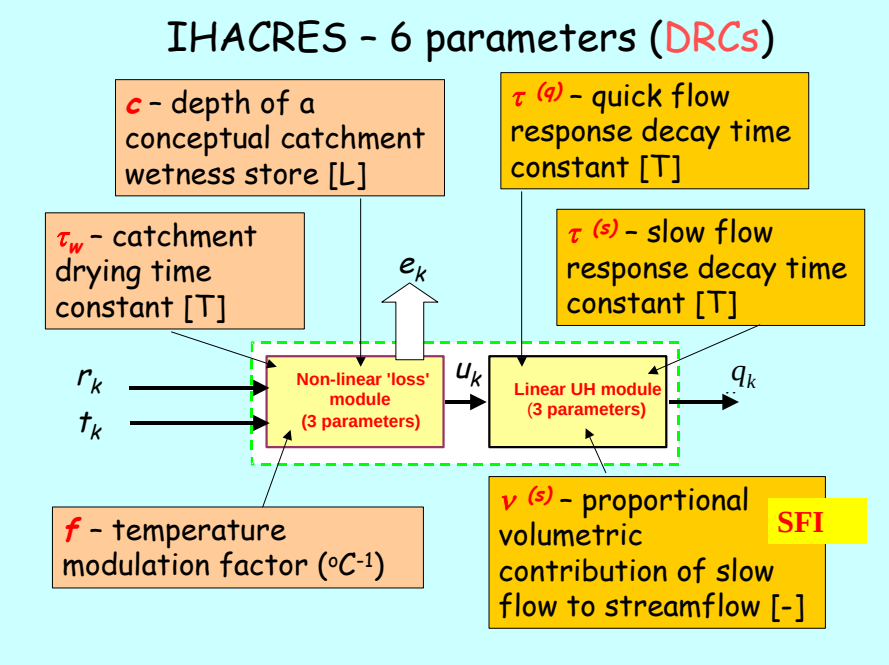


Figure 3: IHACRES overall model structure and DRCs for a (2, 1) model with the JH (1993) loss module

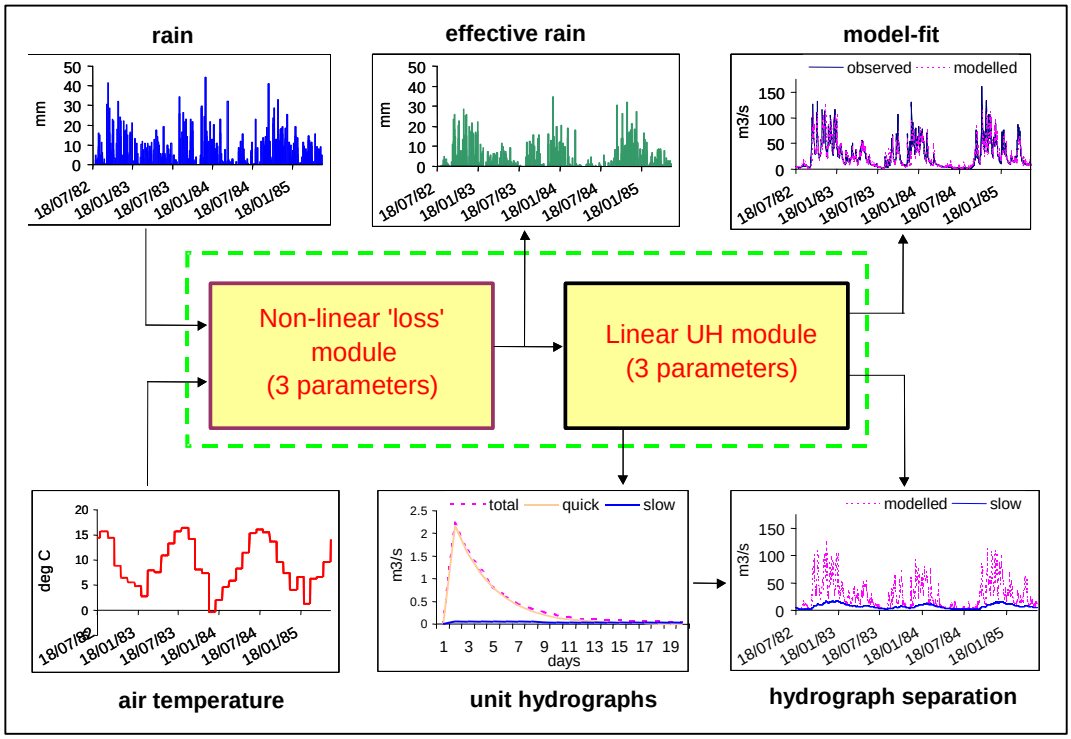


Figure 4: IHACRES UHs and time series inputs and outputs

3. Environmental hydrology and IHACRES

IHACRES has been applied to many catchments in the UK and around the world, for a wide range of environmental hydrology[9] purposes. This Section summarises selected publications under several thematic headings. The work is presented in broadly chronological order within themes, with an emphasis on UK catchments but referring occasionally to catchments elsewhere. The summaries are not meant as substitutes for the original papers cited but serve collectively to illustrate the range of applications and research topics for which IHACRES has been found to be of considerable value. Section 3 is the longest section of the Paper and may be used as a reference source for consultation as required. However, the Section provides a history of IHACRES applications, largely in the context of UK hydrology, which some readers may wish to read from start to finish.

IHACRES applied to different types of catchment

As the first IHACRES results for the small Nant y Gronwen and Nant y Coileth catchments emerged, and shortly after publication of the JLW (1990) paper, the methodology was applied successfully to several other catchments in the UK, Australia and elsewhere.

Employing daily data for a 20 km^2 catchment in the Australian Capital Territory Jakeman *et al*., (1990) show IHACRES UHs for streamflow and its quick and slow components. They also show an IHACRES hourly hydrograph separation for the 0.016 km^2 M6 Maimai catchment in New Zealand. Jakeman *et al*. (1991) and Littlewood and Jakeman (1991a) apply IHACRES to the UK catchments listed in Table 7. Except for the Wye at Gwy Flume (hourly data), the daily flow data used are from the UK National River Flow Archive (NRFA). The results from daily data were encouraging and planning was therefore started for systematic application of IHACRES to NRFA catchments throughout the UK, with a view towards finding statistical links between each DRC and physical catchment descriptors (PCDs), leading to estimation of hydrographs at ungauged sites (see 'Rainfall–streamflow model parameter regionalisation' later in Section 3).

[9] For this Paper environmental hydrology is that which is not engineering hydrology, where the latter usually comprises the application of widely accepted techniques and procedures to assist with the design, construction and safe operation/management of the built environment related to water.

Table 7: Early 1990s applications of IHACRES to UK catchmnents

Catchment	Data timestep	Area (km^2)	BFI*	Annual rainfall (mm	Annual flow (mm)	Flow/Rain (%)
Wye at Gwy Flume (Plynlimon)	hourly	3.9	0.35	2714	2224	82
Monachyle at Balquhidder	daily	7.7	0.18	2575	2109	82
Kenwyn at Truro	daily	19	0.67	1141	644	56
Ettrick Water at Brockhopperig	daily	37	0.34	1904	1591	83
Eden at Temple Sowerby	daily	616	0.38	1170	738	63
Colne at Denham	daily	743	0.87	721	171	24
Teifi at Glan Teifi	daily	894	0.54	1377	1017	74
Lune at Caton	daily	983	0.32	1529	1142	75

Catchment details from CEH (2003)
* Base Flow Index (e.g. Gustard *et al*., 1992)

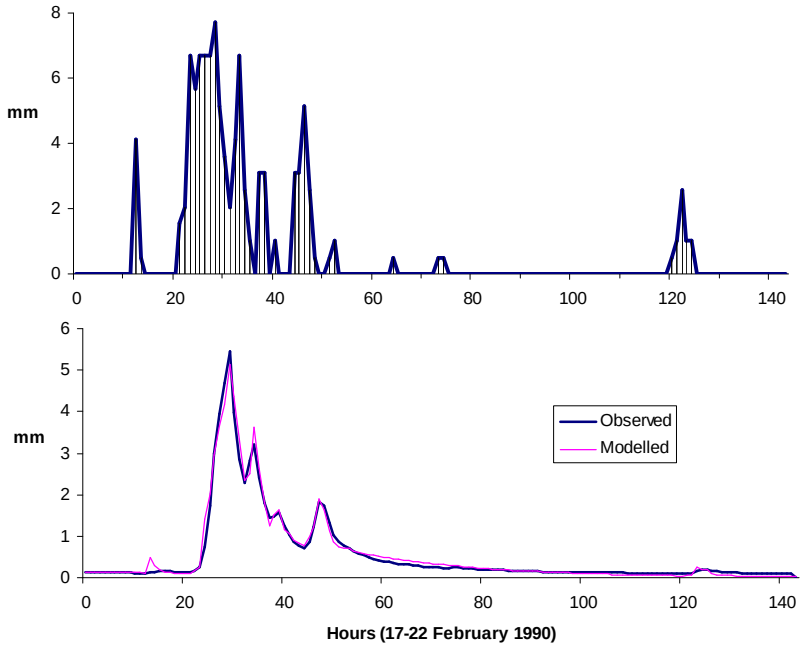


Figure 3: Wye at Gwy Flume: (a) hourly rainfall and (b) streamflow model-fit

Fig. 3 shows hourly rainfall and model-fit to streamflow for the Wye at Gwy Flume (D = 0.98) over a calibration period of 144 hours from 17th to 22nd February 1990. Fig. 4 shows daily rainfall, effective rainfall, model-fit (D = 0.88) and hydrograph separation for the much larger Teifi at Glan Teifi over a model calibration period 26th July 1982 to 29th July 1985. Littlewood and Jakeman (1991a) also mention applications of IHACRES to a 2,344 km^2 basin in the US (daily data) and a small hillslope plot in China using 6 minute interval data. This last item is the artificial 490 m^2 Hydrohill system, an IHACRES analysis for which

was included in a paper on model complexity issues by Jakeman and Hornberger (1993) discussed later in Section 3.

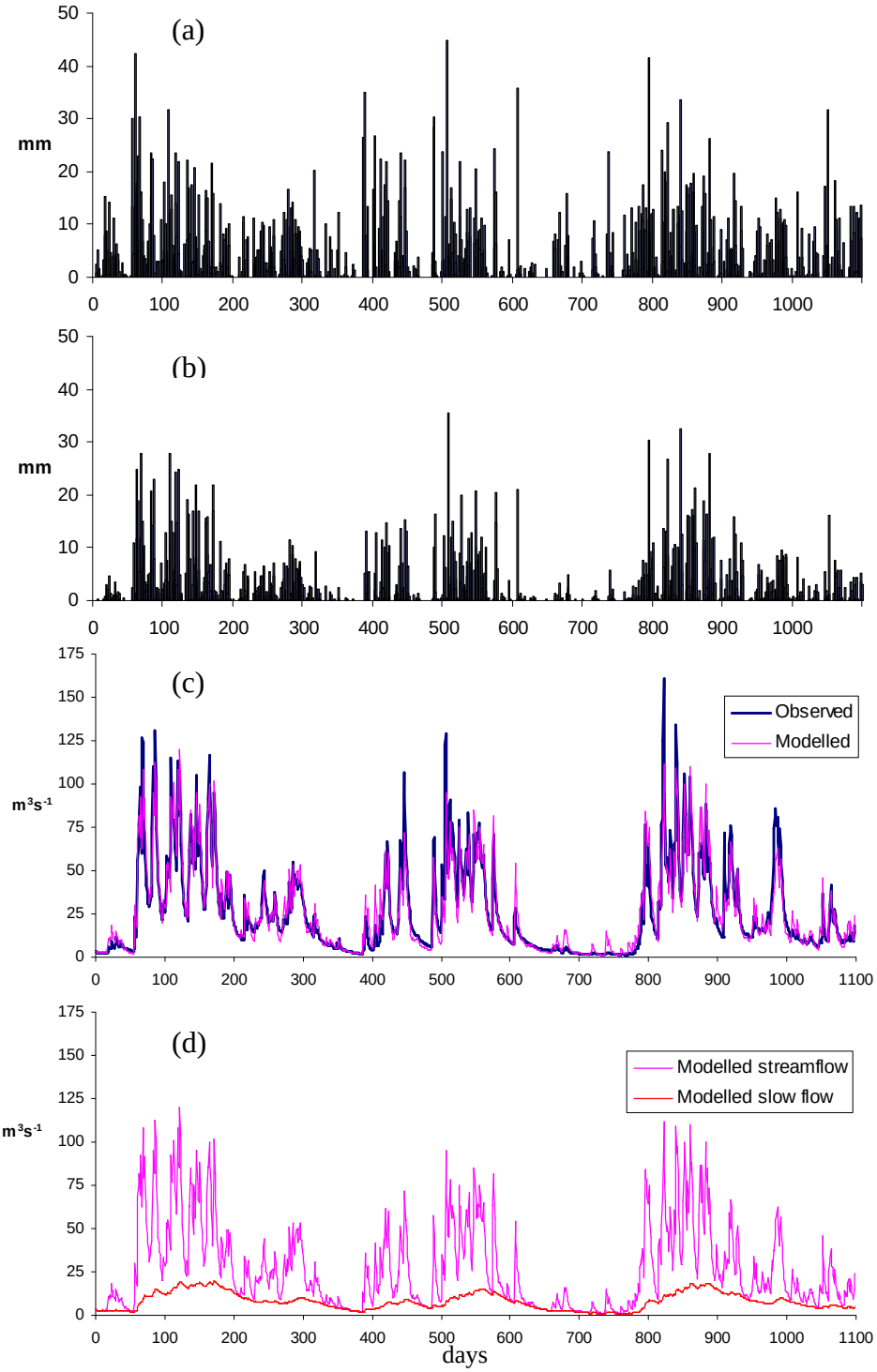


Figure 4: Teifi at Glan Teifi 26th July 1982 to 29th July 1985 (daily): (a) rainfall, (b) effective rainfall, (c) streamflow model-fit and (d) hydrograph separation

The hydrograph separation controversy

IHACRES hydrograph separation, giving dominant quick and slow components of streamflow, invites qualitative, and to some extent quantitative, comparison with hydrograph separation based on field tracer studies. The (2, 1) IHACRES model structure conceptually supports the traditional view that stream water at a hydrograph peak will, unless the peak is a small one superposed on substantial baseflow, comprise mostly quick response water from rainfall, i.e. so-called new water (old water being water that was in the catchment before the rainfall associated with a hydrograph event). In stark contrast, some published tracer studies assert, quite forcefully in some cases, that stream water at the time of a hydrograph peak typically comprises a large proportion of old water, even for wet upland catchments. Declared support for such conclusions includes:

> "… studies of the isotope content of the waters of storm hydrographs … have provided convincing evidence that traditional methods of 'baseflow separation' … are a nonsense" (Beven, 1987).

However, referring to IHACRES hydrograph separation qualitatively and using field measurements of stream electrical conductivity (EC), Littlewood and Jakeman (1991b) argue for the traditional interpretation of hydrographs. They show time series plots that exhibit dilution of Nant y Gronwen stream water during events, except when atmospheric deposition has been relatively high in sea-salts. In the former case, stream EC *decreases* to a sharply defined minimum closely synchronous with the corresponding hydrograph peak. In the latter case, stream EC *increases* to a sharply defined maximum closely synchronous with the hydrograph peak.

Littlewood and Jakeman (1991b) draw attention to these stream EC responses occurring in the order stated above for both the 0.7 km^2 Nant y Gronwen and the 0.8 km^2 Nant y Craflwyn simultaneously (their catchment centres are only about 2 km apart), for consecutive events separated by 6 days in January 1986. (Littlewood (1989) discusses similar stream EC responses for other small catchments draining to Llyn Brianne.) Unfortunately, the stage recorder for the Nant y Gronwen was not operating for the first event. However, stage data for the Nant y Craflwyn which were available for both events indicate that the second event had a substantially smaller peak flow than the first for both catchments.

During the first event Nant y Gronwen EC decreases from about 35 $\mu S.cm^{-1}$ to a sharp minimum of about 26 $\mu S.cm^{-1}$ at peak streamflow, and in the second event the EC increases from about 38 $\mu S.cm^{-1}$ to a sharp maximum of about 49 $\mu S.cm^{-1}$. For the Nant y Craflwyn the corresponding values of stream EC for the first event are 39 $\mu S.cm^{-1}$ decreasing to 33 $\mu S.cm^{-1}$, and 39 $\mu S.cm^{-1}$ increasing to 49 $\mu S.cm^{-1}$ for the second event. A much higher chloride content of bulk deposition[10] for the second event than the first, coupled with consideration of the synoptic air-flow pattern, strongly indicates that much greater sea-salt inputs occurred for the second event than the first (Littlewood, 1989).

Given these observations at peak flows of streamwater dilution (low sea-salt input) and enrichment (high sea-salt input) the dominance of old water at peak flows appears to be unlikely for Llyn Brianne streams. Littlewood and Jakeman (1991b) discuss several shortcomings of a simple mixing model often employed with field tracer measurements to

[10] Wet plus dry deposition, measured at Cwmystwyth about 25 km to the north.

invoke large proportions of old water at hydrograph peaks. The remainder of this section considers further aspects of IHACRES hydrograph separation.

IHACRES hydrograph separations are for modelled flow, so they can be as representative of streamflow components only as far as the goodness of model-fit allows; if the model-fit is not very good the hydrograph separation is unlikely to be good. So, a (2, 1) model with a high D and low %ARPE for a given catchment is more likely to give a hydrograph separation representative of dominant quick and slow components for that catchment than a (2, 1) model for another catchment for which D is low and %ARPE is high.

The precision associated with the more-dominant of the two flow components is typically better than the precision for the other component. This is illustrated in Table 8 where selected results for the 894 km^2 Teifi at Glan Teifi, Wales and the 315 km^2 Eleshnitza at Vaksevo, Bulgaria are reproduced from Littlewood (2000) and Zlatunova *et al*. (2002). As indicated by their SFIs, the catchments have quite different flow regimes; the Teifi, a wet catchment with thin soils over impermeable bedrock, is dominated by quick flow (SFI = 0.269), and the Eleshnitza, which has some karstic features, is dominated by slow flow (SFI = 0.896). There is better precision on the SFI for the Eleshnitza than for the Teifi. Model-fit to streamflow, in terms of D, is better for the Teifi than the Eleshnitza; IHACRES tends to give better model-fits to wet catchments that have a lower proportion of slow flow than quick flow. Although estimates of $\tau^{(q)}$ ($\tau^{(s)}$) for the two catchments are not too dissimilar, the precision associated with $\tau^{(q)}$ for the Teifi (confidence interval -7.4%, +8.4%) is much better than that for the Eleshnitza (-36%, +76%). For $\tau^{(s)}$ the order of the relative magnitudes of precision are reversed, as expected given the relatively much higher SFI for the Eleshnitza. The substantially higher %ARPE for the Eleshnitza corresponds to the overall poorer estimation of UH DRCs for that catchment compared with the Teifi.

Table 8: Model-fit and UH DRCs for the Teifi at Glan Teifi and the Eleshnitza at Vaksevo

Catchment	D	%ARPE	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	SFI
Teifi*	0.882	0.03	2.97 (-7.4%, +8.4%)	39.9 (-23%, +43%)	0.269 (-16%, +17%)
Eleshnitza**	0.742	0.71	2.11 (-36%, +76%)	29.8 (-9.4%, +21%)	0.896 (-9.0%, + 3.9%

Data from Littlewood (2000)

* Calibration period; 26th July 1982 – 29th July 1985; mean annual precipitation and flow are about 1300mm and 960mm (74%) respectively.

** Calibration period 30th September 1986 – 30th September 1988; mean annual precipitation and flow are about 700mm and 214mm (30%) respectively.

(x, y) 95% confidence limits, as percentage departures from the estimated DRC shown.

Rainfall–streamflow model parameter regionalisation

The IHACRES UH for streamflow comprising quick and slow flow acting in parallel, i.e. a (2, 1) model, is defined by the DRCs $\tau^{(q)}$, $\tau^{(s)}$, $v^{(q)}$ and $v^{(s)}$ given earlier in Table 2. Since, by definition, $v^{(q)} + v^{(s)}) = 1$, the UH for a (2, 1) model is completely defined by just three DRCs. The JH loss module (Eqs. 16 to 18) has the 3 parameters c, τ_w, and f, which can also be considered to be DRCs. So, a (2, 1) IHACRES rainfall–streamflow model is completely

defined by just 6 DRCs, which is an attractive degree of parametric parsimony when trying to find statistical relationships between any DRC and physical catchment descriptors (PCDs) such as stream density, main stream length, etc. This process is often referred to as rainfall–streamflow model regionalisation, where the aim is to facilitate estimation of streamflow at ungauged sites. Non-IHACRES UHs have been regionalised for UK catchments, e.g. Nash (1960) and the Flood Studies Report (NERC, 1975).

Jakeman *et al.* (1992) present the case for systematic application of IHACRES for regionalisation, preparing the way for later studies seeking to establish statistical links between IHACRES DRCs and PCDs for groups of catchments in Australia (Post *et al*., 1993; Post and Jakeman, 1996; 1999), the USA (Post *et al*., 1998; Kokkonen, *et al*. 2003) and the UK (Sefton *et al*., 1995; Sefton and Howarth, 1998).

A preliminary investigation was undertaken to explore statistical relationships between each DRC and PCDs for eight small research basins in Wales (two catchments, each with three gauged sub-basins) (Sefton, *et al*., 1995). The two catchments are adjacent in the Plynlimon headwaters of the rivers Wye (at Cefn Brwyn, 10.6 km^2) and Severn (at a trapezoidal flume, 8.7 km^2). The flow-gauged Wye sub-basins range in size from 1.02 km^2 to 3.98 km^2 and those in the Severn headwaters range from 0.89 km^2 to 3.67 km^2. Annual rainfall at Plynlimon is about 2,500 mm. On average, about 87% and 76% of annual rainfall leaves the Plynlimon Wye and Severn catchments respectively as streamflow. During the period of record analysed, the Severn headwater catchment was about 67% conifer forest and the Wye headwater catchment was predominantly moorland grazing (only about 1% conifers); the largely afforested Severn basin above the flume loses more water by evapotranspiration from its predominantly tree cover than is lost from the mainly grass cover in the Wye catchment above Cefn Brwyn. A 6-hourly data timestep was chosen for modelling.

The PCDs considered include area, stream slope, stream density, mean land slope, percentage forest, percentage raw peat, etc. The investigation revealed many interesting qualitative links between DRCs and PCDs, suggesting directions for a regionalisation study to link IHACRES DRCs to PCDs for much larger gauged catchments throughout England and Wales. Applying IHACRES to 60 catchments in England and Wales, ranging in size from about 10 km^2 to about 1,000 km^2, Sefton and Howarth (1998) present a regionalisation study of heroic proportions. Only a brief summary of this work is given here (see Section 10.6 of Beven (2012) for comments about regionalisation generally and for some observations on the paper by Sefton and Howarth (1998)). The JH (1993) loss module is used, and a (2, 1) configuration of quick and slow flow UHs acting in parallel is prescribed for each catchment.

Table 9 gives the correlation coefficient and standard error associated with a regression of each of the DRCs on PCDs. Although several of the correlation coefficients and standard errors are lower or higher, respectively, than desired, Sefton and Howarth (1998) report that for two catchments not included in the set of 60 basins the regionalised model, i.e. using PCDs in regression equations to estimate the DRCs, performs almost as well as an IHACRES model calibrated using hydroclimatological data. For the Marden at Stanley in south-west England an IHACRES model calibrated over the period 1980-1989, gave an R^2 of 0.72 (this R^2 is assumed to be D given by Eq. 14). Using the same rainfall, with DRCs estimated from PCDs for the Marden, the R^2 was 0.61. For the Leven at Leven Bridge the corresponding values of R^2 were 0.56 and 0.53. While these model-fits are not particularly

good they illustrate the principle of applying IHACRES to ungauged basins. Sefton and Howarth (1998) discuss in some detail the PCDs, how they were chosen for inclusion in the regressions and their likely effects on streamflow.

Table 9: Correlation coefficients and standard errors for IHACRES DRCs regressed on PCDs, 60 catchments in England and Wales

	f	τ_w	$1/c$	$\tau^{(q)}$	$\tau^{(s)}$	$v^{(s)}$
Coefficient of correlation	0.80	0.41	0.61	0.64	0.37	0.77
Standard error	0.76	3.41	53.53	0.17	101.3	0.14

Data from Table 6 in Sefton and Howarth (1998)
Units of the standard errors have been assumed to be $^{o}C^{-1}$, days, mm, days, days and dimensionless for the DRCs in the order they appear left to right.

Extending streamflow records

Rainfall time series longer than streamflow time series are often available for specific catchments. For 11 catchments in Scotland, ranging in size from 69 km^2 to 4,407 km^2, Steel *et al*. (1999) calibrate IHACRES models at daily timestep. This modelling forms part of a research project to simulate peak flows from long historical daily precipitation records, the aim being to reassess flood risk for Scottish rivers. In the set of 11 catchments the longest flow record is 63 years and the scheme allows simulation of peak flows over a period 98% longer than this; the shortest flow record is 15 years and peak flows are simulated for a period 647% longer than the measured streamflow record. Snow is sometimes an important component of precipitation for many of the Scottish catchments studied, so a degree-day snowmelt model is applied that was originally developed for use with IHACRES for snow-affected catchments in eastern Victoria, Australia (Schreider *et al*., 1997).

Littlewood and Jakeman (1993) calibrated a model for the 9,948 km^2 Thames at Kingston, using monthly data. The rainfall and naturalised flows are from the NRFA; naturalised flows are gauged flows adjusted by the measuring authority for major abstractions from and discharges to the river. The monthly temperatures employed are from a series representative of Central England. The model is calibrated from August 1953 to September 1989 and is then applied to simulate flows (reasonably well) from August 1884 to April 1951. A key point is that the UH in this case is for a (1, 0) model – attempts to calibrate a (2, 1) model were unsuccessful at that time – so low flows are not modelled too well.

For a subsequent, more detailed, analysis of the Thames at Kingston monthly naturalised flow record, to assist with a reappraisal of the relative severity of historic droughts, a (2, 1) IHACRES model with quick and slow flow components acting in parallel is successfully calibrated (Littlewood and Marsh, 1996). Assuming that Kingston flows measured by the ultrasonic method from 1974 onwards are better than by earlier methods used, the calibration period in this case is from August 1974 to June 1992. Values of D and %ARPE for the (2, 1) model are 0.88 and 0.15 respectively, compared with 0.84 and 0.07 for the (1, 0) model mentioned earlier. The penalty of an increase in %ARPE is considered worthwhile given the increase in D. Furthermore, the (2, 1) model gives a better model-fit to low flows (because it has a slow flow component), which is a key benefit for the analysis of drought streamflows.

Model complexity issues

A paper by Jakeman and Hornberger (1993) extends the model complexity aspects of JLW (1990), where two small catchments are the focus (see Section 2), to several other catchments under a range of hydroclimatological regimes. A finding of their work is that for each of six catchments, a two-component UH for quick and slow flows acting in parallel, i.e. a (2, 1) model, is found to be the best configuration. Table 10 gives details of the six catchments (two of which are in Scotland) that are analysed using daily data. Table 11 reproduces the values for D and %ARPE presented by Jakeman and Hornberger (1993) for (*m*, *n*) models of increasing UH complexity, where the models are calibrated over a period of just one year.

Table 10: Six catchments analysed with different structural complexity for the UH module

Catchment	Data timestep	Area (km^2)	Precipitation (mm/yr)	Annual yield (%)
Orroral Valley, Australian Capital Territory	1 day	89.6	1101	27
Licking Hole, Australian Capital Territory	1 day	20.6	1426	53
Monachyle at Balquhidder, Scotland	1 day	7.7	2953	93
Kirkton at Balquhidder, Scotland	1 day	6.9	2795	88
Coweeta watershed 36, USA	1 day	0.49	2012	64
Coweeta watershed 34, USA	1 day	0.33	2012	46

Unlike for the Nant y Gronwen (Table 5), for which hourly data were used (see Section 2), the maximum D and minimum %ARPE obtained for each catchment in Table 11 do not occur together for a (2, 1) configuration. For all six catchments a (3, 2) configuration gives a higher D than for a (2, 1) configuration but with a much higher %ARPE. The difference in values of D for (3, 2) and (2, 1) configurations is small in most cases. For catchments where a (1, 0) model is better than a (2, 1) model, in terms of both D and %ARPE (e.g. Monachyle), it is because the slow flow fraction is so small that its UH flow component is too difficult for IHACRES to identify (Jakeman and Hornberger, 1993). This problem might be enhanced by the fact that the model calibration period in this case was only one year. Further IHACRES analyses of the Monachyle and Kirkton catchments at Balquhidder (Jakeman *et al*. 1993) are summarised later (see 'Environmental change' later in Section 3). A broad message from Table 11 and the narrative by Jakeman and Hornberger (1993) is that, if maximum D and minimum %ARPE do not occur together (as for the Nant y Gronwen), a (2, 1) UH module is often the configuration of choice on the basis of a trade-off between a high D and a low %ARPE.

Table 11: Model-fits obtained with different UH module structural complexity

Catchment	Configuration $(m, n)^*$	D	%ARPE•
Orroral Valley	(1, 0)	0.761	0.087
	(2, 0)	0.768	3.366
	(2, 1)	0.787	0.108
	(3, 0)	0.788	1.251
	(3, 1)	0.787	945
	(3, 2)	0.785	366
Licking Hole	(1, 0)	0.817	0.033
	(2, 0)	0.824	3.442
	(2, 1)	0.870	0.043
	(3, 0)	0.842	2.013
	(3, 1)	0.854	4.425
	(3, 2)	0.872	104
Monachyle	(1, 0)	0.686	0.492
	(2, 0)	0.686	450
	(2, 1)	0.685	1.555
	(3, 0)	0.690	29.589
	(3, 1)	0.694	34.147
	(3, 2)	0.695	89.647
Kirkton	(1, 0)	0.728	0.175
	(2, 0)	0.728	292
	(2, 1)	0.733	0.278
	(3, 0)	0.740	4.549
	(3, 1)	0.742	836
	(3, 2)	0.746	19,500
Coweeta 36	(1, 0)	0.741	0.074
	(2, 0)	0.749	4.339
	(2, 1)	0.891	0.063
	(3, 0)	0.788	1.502
	(3, 1)	0.893	5.465
	(3, 2)	0.900	7.427
Coweeta 34	(1, 0)	0.808	0.043
	(2, 0)	-	-
	(2, 1)	0.916	0.078
	(3, 0)	-	-
	(3, 1)	0.908	3.264
	(3, 2)	0.922	49.7

Data from Jakeman and Hornberger (1993).

- Jakeman and Hornberger (1993) report divergent model calibrations.

• For presentational purposes some of the ARPE values are given with only 2 significant figures.

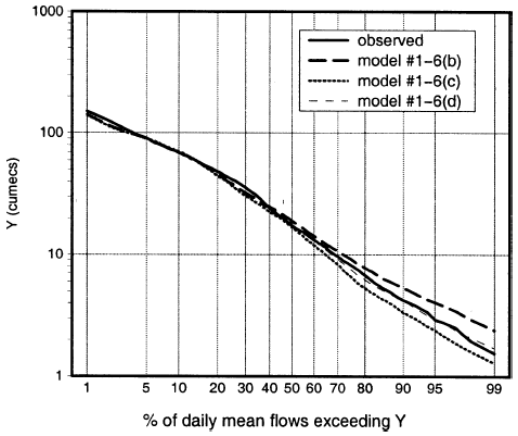
Concerning the level of justifiable complexity in a loss module preceding an IHACRES UH module, Littlewood (2002b) performs an experiment using a published 6-parameter soil-vegetation-atmosphere-transfer (SVAT) module (Roberts and Harding, 1996) in series with a 3-parameter (2, 1) IHACRES UH module. The resultant 9-parameter rainfall–streamflow model is applied to the 0.65 km^2 Kimakia 'C' catchment in Kenya, where the dominant vegetation is bamboo. Daily data from 4th October 1968 to 18th November 1971 are used for model calibrations. A longer record, from 24th February 1959 to 30th June 1974, is used for model simulations.

Values for the 6-parameters of the SVAT module had been estimated for bamboo vegetation (Roberts and Harding, 1996), using soil moisture measurements. Employing these values (Kimakia 'C' was assumed 100% bamboo) with an input of daily rainfall, the SVAT module generates daily effective rainfall. The effective rainfall is then used with observed streamflow to calibrate a (2, 1) IHACRES UH module, giving a 9-parameter SVAT-UH model. In terms of D and %ARPE the 9-parameter model performs better over the calibration and simulation periods than a 'standard' 6-parameter IHACRES model incorporating the JH (1993) loss module. This indicates the benefit of the soil moisture data used by Roberts and Harding (1996) to develop the SVAT module for bamboo vegetation. Sequential simplification of the SVAT module structure is undertaken by Littlewood (2002b) to give 8-, 7- and 6-parameter SVAT-UH models; in each case adjustments are made to the remaining SVAT module parameter values. There are points of detail about the SVAT module, its sequential simplification and the quality of the SVAT-UH model-fits to streamflow, described in Littlewood (2002b), which this short summary cannot cover adequately. However, a broad conclusion is that there appears to be no statistical advantage, in terms of rainfall–streamflow model-fit for Kimakia 'C', of the SVAT module having more than 3 parameters.

Multi-objective model-fitting

When calibrating a rainfall–streamflow model for anything other than preliminary work, selecting a best model on the basis of a single model-fit criterion, e.g. D, is often not good practice. With IHACRES, a trade-off between D and %ARPE is demonstrably better than relying solely on D. However, depending upon the purpose of the modelling, application of additional model-fit criteria can be worthwhile, as the following example illustrates.

Littlewood (2002c) shows that low flows for the Teifi at Glan Teifi tend to be overestimated by an IHACRES model calibrated solely on the basis of a D-%ARPE trade-off. Model-fit to Teifi flows greater than the median is good (see Fig. 5). Using the D-%ARPE calibrated model as a starting point, it is found that loss module parameter *f* (in Eq. 18) can be



Note: The three FDCs for modelled flows (b), (c) and (d) correspond to different trial-and-error values of parameter *f* in the loss module. FDC (d) is a good match to observed flows over the 1-percentile to 99-percentile range. See Littlewood (2002c) for details.

Figure 5: Teifi at Glan Teifi flow duration curves for observed and modelled streamflow using different values of UH DRC *f*

adjusted by trial-and-error to give a much better match between the low-flow ends of flow duration curves (FDCs) for observed and modelled flows. This can be achieved with barely discernible changes to the FDC for modelled high flows greater than the median, as shown in Fig 5. The quick flow constant, $\tau^{(q)}$, decreases by only about 4% but $\tau^{(s)}$ decreases by about 20%.

Littlewood (2003) repeated this exercise for six other catchments; five other Welsh catchments and the Teme at Knightsford Bridge in the English West Midlands (the Teme has a small portion of its upper catchment in Wales). Table 12 lists the seven catchments, i.e. including the Teifi, with basic hydrological details, and Figs. 6 and 7 show FDCs for the six additional catchments. All seven catchments were modelled using daily rainfall and streamflow data.

Table 12: UK catchments employed to investigate an enhanced model selection procedure

Catchment	Area (km^2)	BFI*	Annual rainfall (mm	Annual flow (mm)	Flow/Rain (%)
Gwili at Glangwili	129	0.46	1628	1180	72
Irfon at Cilmery	244	0.39	1673	1275	76
Cothi at Felin Mynachdy	298	0.43	1645	1191	72
Conwy at Cwm Llanerch	344	0.28	2189	1688	77
Teifi at Glan Teifi	894	0.54	1355	997	73
Tywi at Nantgaredig	1090	0.46	1574	1107	70
Teme at Knightsford Bridge	1480	828	366	44	44

Catchment details from CEH (2003)
* Base Flow Index

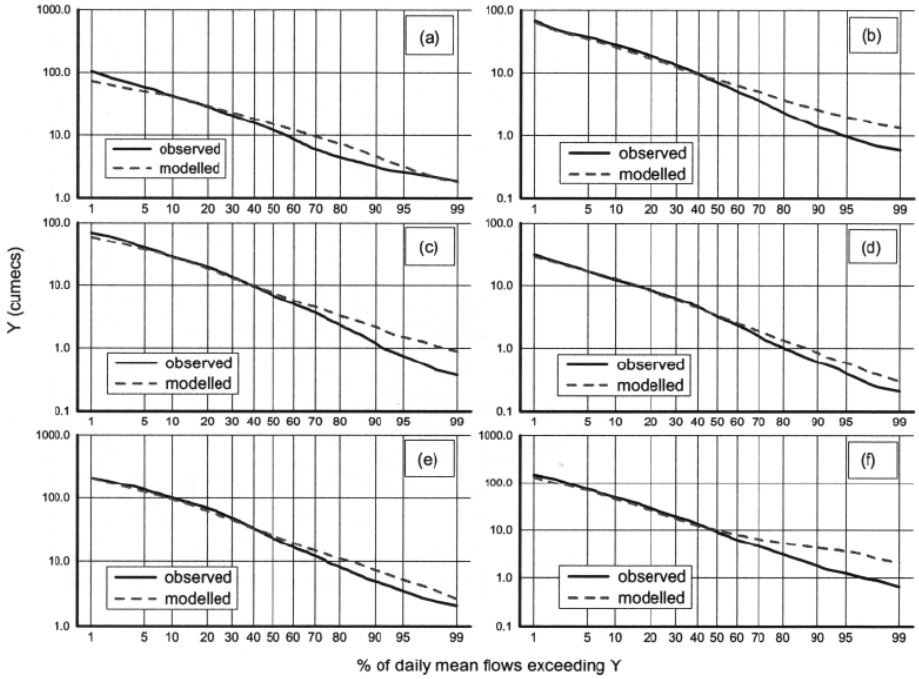


Figure 6: Flow duration curves for observed and modelled streamflow (*f* unadjusted): (a) Teme at Knightsford Bridge, (b) Irfon at Cilmery, (c) Cothi at Felin Mynachdy, (d) Gwili at Glan Gwili, (e) Tywi at Nantgaredig, and (f) Conwy at Cwm Llanerch

Fig. 6 shows that for five of the six additional catchments, i.e. the Irfon, Cothi, Gwili, Tywi and Conwy, models calibrated on the basis of a trade-off between D and %ARPE tend to overestimate low flows, as occurs for the Teifi. For the Irfon, Cothi, Gwili and Tywi, Fig. 7 shows that models calibrated using the additional adjustment of loss module parameter *f* as described above have much better fit at low flows, without impairing model-fit at high flows (though $\tau^{(q)}$ for the Gwili, for example, decreases by about 30%). The FDCs for the Teme and the Conwy do not tell quite the same story but Littlewood (2003) suggests reasons for this, e.g. low flows for the Teme are perhaps sustained from valley gravel storage, and daily data are probably too coarse for modelling the flashy Conwy (data timestep issues are discussed later in Section 3). With the additional adjustment of *f*, values of $\tau^{(s)}$ for the Irfon, Cothi, Gwili and Tywi decrease, corresponding to the steeper, better modelled FDCs at low flows shown in Fig. 7 compared with Fig. 6.

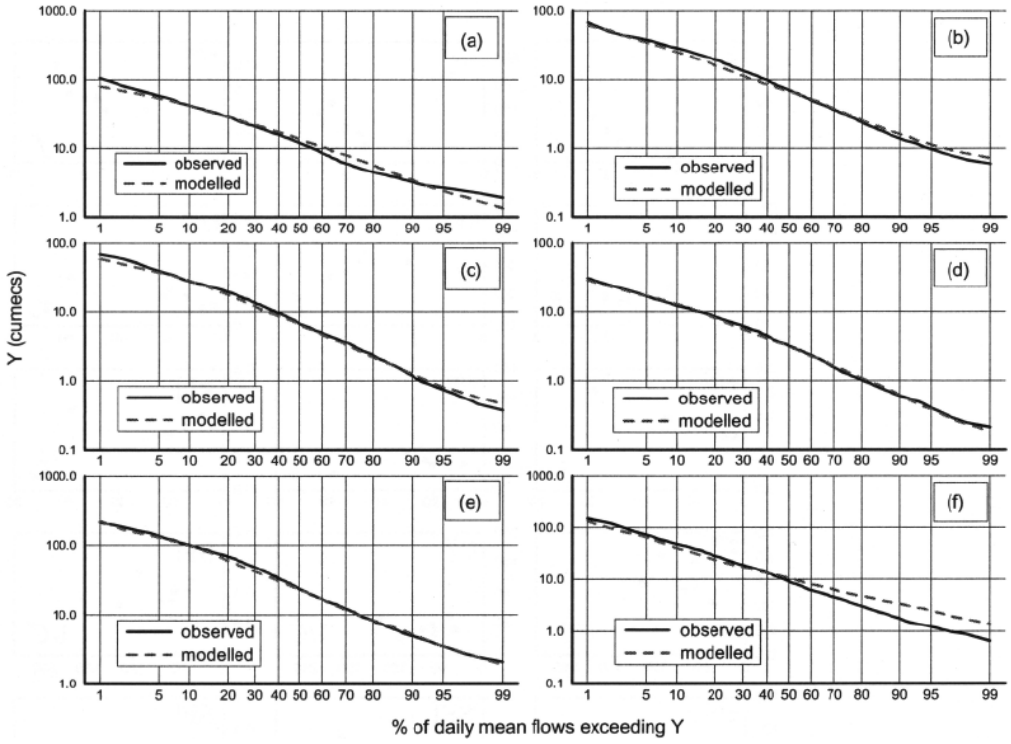


Figure 7: Flow duration curves for observed and modelled streamflow (*f* adjusted): (a) Teme at Knightsford Bridge, (b) Irfon at Cilmery, (c) Cothi at Felin Mynachdy, (d) Gwili at Glan Gwili, (e) Tywi at Nantgaredig, and (f) Conwy at Cwm Llanerch

These results serve as a reminder that when values of IHACRES DRCs estimated from rainfall, streamflow and temperature data for groups of catchments are used for further modelling work, e.g. model parameter regionalisation, care should be taken to check that the estimated DRCs are sufficiently consistent for the intended purpose. If, say, values of $\tau^{(s)}$ from the D-%ARPE trade-off procedure are biased (inaccurate), as for the Teifi, Irfon, Cothi, Gwili and Tywi, it could account for some of the imprecision in a statistical DRC-PCD relationship for that DRC. It is better to use DRCs that have been calibrated using additional

criteria, e.g. adjustment of *f* to give better model-fit to the low flow end of FDCs (and therefore less-biased values of $\tau^{(s)}$).

There can also be uncertainty in DRCs because of the period of record used for model calibration, as shown in Table 13. The Conwy results illustrate another interesting issue; the calibrated values for $\tau^{(q)}$ of less than 1 day indicate that daily data are too coarse for this very wet, flashy catchment. Given that $\tau^{(q)}$ and $\tau^{(s)}$ are estimated simultaneously by IHACRES, it is likely that when $\tau^{(q)}$ is poorly estimated $\tau^{(s)}$ will be too. This appears to be what has occurred for the Conwy; adjustment of *f*, as an additional criterion to a D-%ARPE trade-off, does not improve the match between FDCs as successfully as it does for the catchments where $\tau^{(q)} > 1$. The next sub-section discusses in more detail how IHACRES can reveal insights to the effects of data timestep on calibrated rainfall–streamflow model parameters.

Table 13: IHACRES model-fit and DRCs for models calibrated over different periods of record

Catchment	δ (days)	f ($^oC^{-1}$)	τ_w (days)	D	Bias (m^3s^{-1})	%ARPE	1/c (mm)	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	SFI
Gwili	-	1.2	2	0.851	0.14	0.05	31	1.70	32.2	0.46
	0	1.1	14	0.822	0.01	0.02	86	1.90	44.2	0.37
Irfon	-	2.3	9	0.825	0.07	0.07	83	1.34	26.5	0.42
	0	0	6	0.751	0.14	0.03	59.8	1.52	49.3	0.45
Conwy	-	1.1	2	0.778	0.88	0.13	30.1	0.87	35.0	0.40
	0	0.2	9	0.779	0.50	0.03	104	0.98	117	0.30
Teifi	-	0.1	9	0.818	0.08	0.04	63.5	2.99	89.5	0.35
	1	1.1	22	0.857	0.32	0.01	99.3	1.99	48.8	0.38

Top rows: models calibrated by Sefton and Howarth (1998), over approximately 3-year periods within September 1986 – August 1989.

Bottom rows: models calibrated by Littlewood (2003) using the D-%ARPE trade-off method, over the approximately 8-year period 9th May 1980 – 25th June 1988.

Data timestep issues

The values of DRCs calibrated using data at a given timestep depend on that data timestep. Employing a (2, 1) model for the Wye at Cefn Brwyn with $f = 0$ (i.e. just 5 DRCs) there are well-defined qualitative relationships between each calibrated DRC and the data time-step employed for its calibration (Littlewood, 2007; Littlewood and Croke, 2008), as shown in Fig. 8 where the error bars are indicative 95% confidence limits. The models, calibrated over the period 6th December 1987 to 2nd July 1988, are given in Table 14. As the data timestep decreases the model-fit in terms of D stays about the same but the UH is identified with better precision (lower %ARPE).

Littlewood and Croke (2008, 2013) and Littlewood *et al.* (2010) extend this analysis, exposing the massive inaccuracy that can occur in a precisely estimated $\tau^{(q)}$ for the Wye at Cefn Brwyn when daily data are used. The precision in $\tau^{(q)}$ estimated from daily data is about ±2%. However, the corresponding accuracy, relative to the value of $\tau^{(q)}$ calibrated using hourly data, is about +430%. This arises from the loss of information in daily rainfall and streamflow data, which is too coarse a temporal resolution with respect to the quick response

dynamics of the system. For a given data timestep this inaccuracy will vary between catchments because of their different dynamic response times.

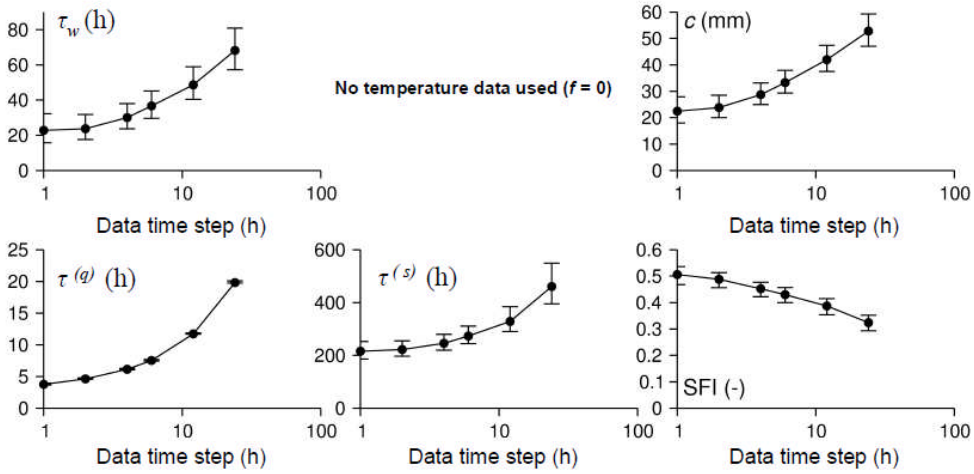


Figure 8: Wye at Cefn Brwyn DRCs estimated using different data timesteps

Table 14: Wye at Cefn Brwyn model-fit and DRCs calibrated using different data timesteps

Data timestep (hours)	τ_w (hours)	c (mm)	$\tau^{(q)}$ (hours)	$\tau^{(s)}$ (hours)	SFI (-)	D	%ARPE
24	67.2	52.2	19.8	455	0.326	0.895	0.142
12	48.0	41.6	11.7	325	0.389	0.907	0.044
6	37.2	33.6	7.54	275	0.428	0.910	0.017
4	30.4	28.9	6.14	247	0.450	0.905	0.010
2	24.0	24.0	4.63	223	0.487	0.910	0.003
1	23.0	22.5	3.76	216	0.505	0.905	0.001

Data from Littlewood and Croke (2008)

Littlewood and Croke (2013) estimate that for the Wye at Cefn Brwyn about 42% and 58% of the absolute inaccuracy in (daily) $\tau^{(q)}$ are due to losses of information in effective rainfall and streamflow daily data respectively. For $\tau^{(s)}$ estimated from daily data, the IHACRES precision, at about ±12%, is poorer than for $\tau^{(q)}$ but its accuracy, while still large at about +110%, is better. About 85% and 15% of the absolute inaccuracy in $\tau^{(s)}$ was found to be due to losses of information in effective rainfall and streamflow daily data respectively.

Each DRC curve in Fig. 8 plots as an approximately straight line when the time axis is arithmetical (not shown). Extrapolation of the straight lines for $\tau^{(q)}$, $\tau^{(s)}$ and $v^{(s)}$ to a data timestep of zero gives instantaneous unit hydrograph (IUH) values for those DRCs. For the Wye at Cefn Brwyn extrapolation of the loss module DRCs (τ_w and c) to a data timestep of zero completes an instantaneous rainfall–streamflow model. Ideally, in any analysis to quantify and compare differences between DRCs for sets of catchments, e.g. for regionalisation studies, normalized (instantaneous) values of DRCs should be used, with the

expectation this will give better precision in DRC-PCD relationships than obtained with non-normalised DRCs (Littlewood, (2013). To date, only non-normalized IHACRES DRCs have been employed for studies leading to DRC-PCD relationships for UK catchments.

Environmental change

Land-use change and other interventions

Jakeman *et al*. (1993a) apply IHACRES to a paired-catchment study at Balquhidder, Scotland. In the 7.7 km^2 Monachyle catchment there had been clear-felling of trees, and in the 6.9 km^2 Kirkton catchment there had been some drainage ditching followed by planting of trees. Comparisons are made for each catchment of quick and slow flow UH DRCs for consecutive 12-month periods before, during and after the land-use changes. The analyses employ daily data, and the 12-month periods are the same for each catchment.

On the basis of 90% confidence intervals for the UH DRCs, the $\tau^{(q)}$ values for the two catchments are significantly different. Differences between the $\tau^{(s)}$ DRCs for the two basins are not so clear-cut. The analysis does not detect any effects on the UH DRCs of the partial land-use changes in either of the Balquhidder catchments. However, the work demonstrates the principle of using IHACRES to detect and quantify the effects on streamflow of land-use change, or any other intervention that might affect streamflow dynamics, e.g. so-called natural flood management, NFM, practices. An important point raised by this study is that, if the objective is to detect and quantify from hydrometric measurements the effects of an environmental change, the magnitude of the change needs to be substantial. A land-use change affecting only a modest proportion of a catchment may not generate a signal sufficiently strong at catchment-scale to be detectable with useful confidence.

Climate change

Jakeman *et al.* (1993b) discuss several aspects of modelling changes in streamflow caused by possible future climate change. To give a methodology that could be applied to many catchments, and provide an indication of the uncertainties involved, they apply IHACRES to assess the effect of a rise in air temperature on mean streamflows for the 894 km^2 Teifi at Glan Teifi and the 767 km^2 French Broad River at Blantyre, North Carolina. For an increase of 1^{o}C, average streamflow is estimated to decrease by between about 2% and 6% for the Teifi, and by between about 4% and 7% for the French Broad River. Several suggestions are made concerning further possible work of this nature.

Sefton and Boorman (1997) calibrate IHACRES models for 39 catchments in England and Wales with areas less than 1,000 km^2. They use IHACRES to estimate the effects of different climate change scenarios on three indices of streamflow: the mean; the flow exceeded 95% of the time (Q95); and the mean of annual (water-year) maximum daily flows. Climate change scenarios from two global circulation models (GCMs) are applied. They also establish DRC-PCD relationships (with variable success for the six DRCs), with a view towards estimating the effects of climate change on streamflow at ungauged sites.

The breadth of the work by Sefton and Boorman (1997) is notable. For many reasons, some of which they discuss, the uncertainty in an estimate of the change in any streamflow statistic in response to an uncertain future climate change is likely to be un-quantifiably huge, e.g. because of the uncertain political dimensions of future emissions and the uncertainties

associated with GCMs. This type of estimation is futurology, which surely has its place, rather than predictive hydrology.

Applying a simple sensitivity test, Boorman and Sefton (1997) expose the artefact that, irrespective of catchment, IHACRES featuring the JH (1993) loss module gives a hydrologically unacceptable 21% increase in modelled mean streamflow for a 10% increase in rainfall. Similarly, a 10% decrease in rainfall gives an unacceptable 19% decrease in modelled mean streamflow for any catchment. Clearly there is a problem with the JH (1993) loss module. However, it is worth noting that the sensitivity test applied by Boorman and Sefton (1997) is unrealistic hydrologically. If a 10% increase (or decrease) in rainfall comprises seasonally-varying percentage changes in rainfall that give an overall 10% increase (decrease) in rainfall each year (i.e. different seasonal profiles for different catchments – see Table 3 in Sefton and Boorman (1997) for an example), the JH (1993) loss module within IHACRES generates different changes in mean streamflow for different catchments, not a uniform 21% increase (19% decrease) across all catchments. In practice therefore, the JH (1993) loss module within IHACRES can provide useful guidance on the likely effects on streamflow of modest and sensible projected changes in rainfall and temperature regimes – but not for the unrealistic 'step change' as in the sensitivity test invoked by Boorman and Sefton (1997). This point is re-visited in Section 6 'Concluding remarks'.

For a study of the potential for hydropower generation in the upper reaches of the Severn in mid-Wales, Carless and Whitehead (2013) employ IHACRES (including the JH (1993) loss module) to estimate seasonal changes in streamflow corresponding to climate change scenarios. Whitehead and Edmunds (2012) use the same IHACRES model structure, with GCM reconstructions of past climate, to investigate the palaeohydrology of the upper Kennet. This work was undertaken to assist with an assessment of the basic water resources available in the upper Kennett around 4,400 BP to support the people who built Silbury Hill, Wiltshire.

IHACRES with the JH (1993) loss module can, therefore, be used to generate indicative estimates of the likely effects on streamflow of some climate change projections (the more realistic the better). Loss modules for IHACRES other than the JH (1993) module are discussed later in Section 3 (see 'Loss modules in IHACRES').

Streamflow forecasting

As far as is known, IHACRES has not been applied for forecasting UK streamflows but the following example, for catchments in Brazil (Littlewood *et al*., 2006, 2007a), illustrates its potential utility for such work generally. The example also serves to show application of IHACRES to much larger catchments than we have in the UK. Tables 15 and 16 give selected details of four Brazilian catchments and results from IHACRES modelling respectively.

Interaction between surface (including near-surface) water with the regional Guarani Aquifer System probably affects the flow regimes at the four gauging sites to different degrees. Comparative visual inspection of multi-year hydrographs for the four catchments, shown in the 2006 paper, and the combination of a high BFI with a very high 1/c for the R. Preto (Table 16), suggests that the R. Preto is particularly affected by interactions with the regional groundwater system.

Table 15: Four Brazilian catchments

Catchment	Area (km^2)	Mean annual rainfall 1980-2001 (mm)	Mean annual streamflow 1980-2001 (% of rainfall)
R. dos Bois at Barra do Rio Verde	30,491	1447	31
R. Ivaí at Novo Porto Taquara	34,414	1607	44
R. Meia Ponte at Ponte Meia Ponte	11,483	1572	25
R. Preto at Quirinópolis	1,657	1422	28

Table 16: Brazilian catchment model-fits and DRCs

Catchment	δ (days)	D	τ_w (days)	f ($^oC^{-1}$)	$1/c$ (mm)	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	$v^{(q)}$ (days)	BFI
R. dos Bois	1	0.90	52	0	912	8.7	178	0.59	0.84
R. Ivaí	1	0.83	20	0.112	246	4.9	128	0.34	0.63
R. Meia Ponte	1	0.87	52	0	1,104	6.5	124	0.63	0.81
R. Preto	0	0.78	1040	0	13,698	5.3	387	0.81	0.88

Littlewood *et al*. (2007a) present detailed analyses of the Rio Ivaí and Rio dos Bois. For these two catchments, the performance of IHACRES is first compared with that of the spatially-distributed model MGB (Modelo de Grandes Bacias) which was developed at the Instituto de Pesquisas Hidráulicas (IPH) of the Brazilian Federal University UFRGS (Allasia *et al*., 2005; Collischonn *et al*., 2005). IHACRES models are calibrated over the period used by Collischonn *et al*. (2005) to calibrate the GMB models. Table 17 reproduces information from Table 5 in Littlewood *et al*. (2007a), showing that the simpler IHACRES model compare favourably with the MGB model for both catchments – indeed, there appears to be no distinguishable difference between the two model-fits for the R. dos Bois.

Table 17 : Comparison of MGB and IHACRES model-fits for two Brazilian catchments

Catchment	Coefficient of determination D		Bias delta V (%)	
	MGB	IHACRES[c]	MGB	IHACRES[c]
Calibration				
R. dos Bois[b]	0.87	0.87	1.8	0.7
R. Ivaí[a]	0.84	0.80	-3.0	2.4
Validation				
R. dos Bois[b]	0.91	0.91	-6.3	-6.3
R. Ivaí[a]	0.86	0.81	2.7	8.8

[a] Calibration 1996-2001 (1995 warm-up); validation 1988-1995

[b] Calibration 1991-2001 (1990 warm-up); validation 1981-1990

[c] Excluding warm-up period over calibration periods

The second part of the work on the R. dos Bois and R. Ivaí is concerned with streamflow forecasting, specifically to assess the value of daily rainfall forecasts from a regional numerical weather-prediction model (ETA, named after the coordinate system used). From 3 January 1996 to 28 December 2001, forecasts of daily rainfall are available for each Wednesday of the current week to Friday of the following week, giving 312 sets of 10-day rainfall forecasts for each catchment. Using the recorded daily rainfall and streamflow up to

and including the Tuesday of each week (day 0 before each 10-day forecast period), daily streamflows are forecast in four ways (a–d), as follows.

Commencing 3rd January 1996, IHACRES models are applied recursively in simulation-mode over each of the 312 10-day periods (a) using the 10-day daily rainfall forecasts, (b) assuming there was no rain over each 10-day period, (c) assuming rainfall for each of the 10 days is the mean rainfall for that day of the year calculated over the 16-year period 1980-1995; and (d) assuming the rainfall is known. A straightforward one-step-ahead forecast by recursive application of Eq. 19 (Section 2), is used as a benchmark. There are several interesting results. For example, forecasts of daily flows for 2 to 10 days ahead for the R. dos Bois using rainfall forecasts are as good as if the rainfall had been known. For the R. Ivaí, streamflow forecasts 2 to 5 days ahead are poorer than if the rainfall had been known, then for 6 to 10 days ahead slightly better than or about the same as if the rainfall had been known.

The forecasting work outlined above uses IHACRES models calibrated over the approximately 15-year period from 1st January 1981 to 2nd January 1996, i.e. before rainfall forecasts were available. The parameters of the models are fixed thereafter for the 312 sets of 10-day periods. As discussed by Littlewood *et al.*, (2007a), further work towards an operational procedure for flow forecasting could involve (a) updating the IHACRES model parameters as new observations of rainfall and flow become available and (b) supplementary modelling of the residuals.

Chalk stream and other groundwater-dominated flow regimes

Littlewood (2020) investigates the utility of IHACRES for modelling the daily flows of three springs at the base of the Chalk Downs escarpment in southern Oxfordshire, each spring marking the start a stream that flows towards the middle reaches of the Thames. Streamflow is gauged a short distance downstream of each spring; Letcombe Brook at Letcombe Bassett, Mill Brook at Blewbury and Ewelme Brook at Ewelme. The BFIs are 0.96, 0.96 and 0.97 respectively and, in the same order, the nominal areas associated with the springs are 4.0 km^2, 2.0 km^2 and 13.4 km^2 (Marsh and Lees, 2003). Analyses of hydrometric

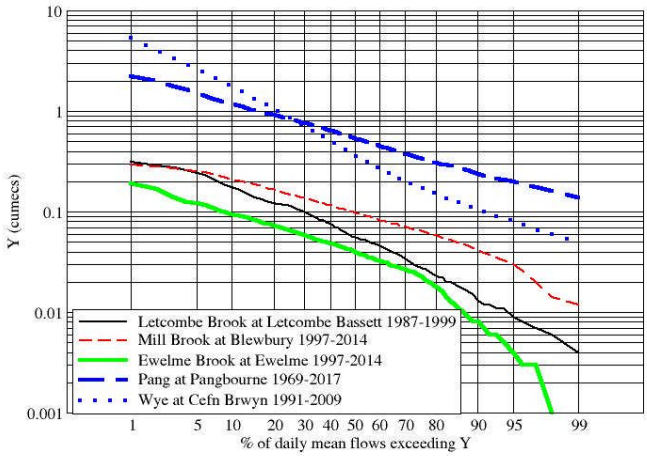


Figure 9: Flow duration curves

data show that while 13.4 km^2 is a reasonable recharge area for Ewelme Brook at Ewelme, 4.0 km^2 and 2.0 km^2 are too small for Letcombe Brook at Letcombe Bassett and Mill Brook at Blewbury respectively; analysis of annual rainfall and streamflow data for the Brooks and other catchments in the region indicates recharge areas of about 23 km^2 to Letcombe Bassett and about 30 km^2 to Blewbury.

Figure 9 shows flow duration curves (FDCs) for the three Brooks at their gauging sites and, for comparison, FDCs for the Chalk-affected Pang at Pangbourne (171 km^2, BFI = 0.87) and the non-Chalk Wye at Cefn Brwyn (10.6 km^2, BFI = 0.31). Average annual rainfalls for the four Chalk-affected catchments are between about 650mm and 730mm, and for the Wye at Cefn Brwyn the average annual rainfall is about 2,490 mm. The high BFI for the Pang (but not as high as for the Brooks) is because of substantial amounts of groundwater from the dip slope of the Chalk to the north of the escarpment above the springs at Letcombe Bassett, Blewbury and Ewelme. The relatively low BFI of 0.31 for the Wye at Cefn Brwyn reflects the dominance of surface and near-surface flow pathways in that catchment, compared with the dominance of deep flow pathways in the catchments above the springs and in the upper parts of the Pang basin. Whereas the FDCs for the Pang and the Wye are approximately log-normal, i.e. they plot nearly as straight lines using those axis scales, the FDCs for the Brooks are convex upwards, most markedly for Ewelme Brook.

A (2, 1) model for the Pang at Pangbourne, calibrated using daily data from 22nd September 1997 to 30th December 2017, has D = 0.749 and %ARPE = 0.003; Fig. 10 shows the corresponding simulation model-fit from 1969 to 2017 (the lower panel shows the model residuals). The SFI for the Pang at Pangbourne of 0.78 is consistent with a flow regime heavily influenced by groundwater.

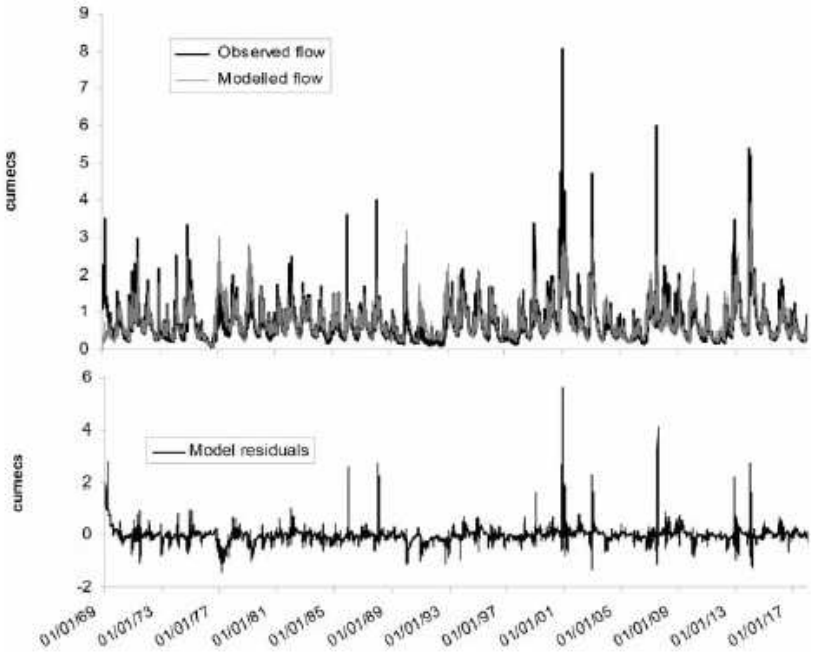


Figure 10: Pang at Pangbourne model-fit 1969-2017

IHACRES fails to calibrate a (2, 1) model for Ewelme Brook and Letcombe Brook but (1, 0) models are calibrated for those Brooks. A (2, 1) model is calibrated for Mill Brook (SFI = 0.99) but it is no better statistically than a (1, 0) model because the quick flow component is too small (on average only about 1% of the streamflow volumetrically) to be identified reliably. Table 18 gives the (1, 0) models calibrated for the three Brooks. Figs. 11 and 12 show plots of input data and model-fits for the three Brooks.

Table 18: Chalk Brook model-fits and DRCs

Catchment	τ_w (days)	f ($^0C^{-1}$)	c (mm)	τ_1 (days)	β (m^3s^{-1})	D	%ARPE
Mill Brook at Blewbury	1.7	3.3	255	112	0.009	0.849	<0.0005
Ewelme Brook at Ewelme	2.4	5.8	822	118	0.008	0.798	<0.0005
Letcombe Brook at Letcombe Bassett	1.7	4.9	673	50.2	0.020	0.759	<0.0005

Data from Table 2 in Littlewood (2020)

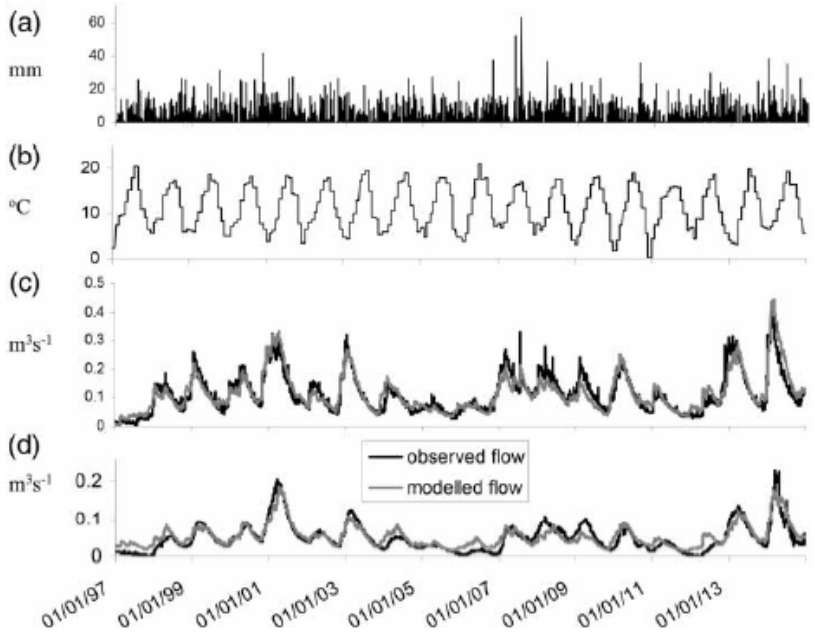


Figure 11: Rainfall, air temperature and streamflow 1997–2014; (a) Mill Brook daily rainfall, (b) Oxford monthly air temperature, (c) Mill Brook observed and modelled daily streamflow and (d) Ewelme Brook observed and modeled daily streamflow

Further work is required to investigate the efficacy of different loss modules within an IHACRES framework for groundwater-dominated catchments in the UK. Relative to other countries around the world, the UK has a large number of chalk catchments gauged for streamflow. The examples outlined here indicate that it could be worthwhile, as a starting

point in an analysis of such catchments, applying IHACRES featuring the JH (1993) loss module to all gauged UK chalk catchments.

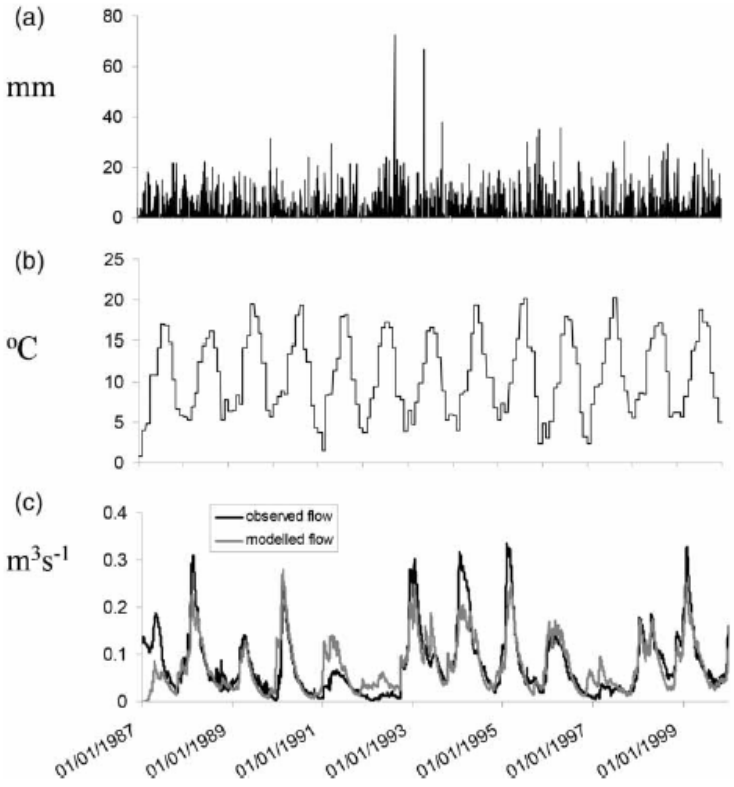


Figure 12: Rainfall, air temperature and streamflow 1987–1999; (a) Letcombe Brook daily rainfall, (b) Oxford monthly air temperature and (c) Letcombe Brook observed and modelled daily streamflow

Loss modules in IHACRES

JLW (1990) introduce IHACRES using the loss module given by Eqs. 1, 2 and 4 (Section 2), which was first applied by Whitehead *et al*. (1979) for modelling Bedford-Ouse streamflow. As mentioned earlier, for the PC-IHACRES software package the JH (1993) loss module superseded the JLW (1990) loss module. To date, it is the JH (1993) loss module within an IHACRES framework that has been applied most widely to UK catchments.

The care with which the JH (1993) loss module should be applied to assist with climate change work has been discussed earlier in Section 3. Another less-than-perfect feature of the JH (1993) loss module is that for some catchments and calibration periods it can generate values of catchment wetness index, s_k (Eq. 1), that are occasionally greater than 1. This gives values of effective rainfall, u_k, greater than the rainfall, r_k, which is

unreasonable hydrologically. However, this behaviour is considered to be acceptable pragmatically for many applications provided that the values of $s_k > 1$ are only slightly greater than 1 on a small number of occasions. Given the large uncertainty that can occur in estimates of catchment storm rainfall due to spatial variability of rainfall, low raingauge density and a tendency for conventional raingauges to undercatch during storms when high wind speeds often occur, occasional $u_k > r_k$, are considered relatively unimportant.

It is important to note, though, that frequent $s_k > 1$, by large amounts, can occur with IHACRES (with the JH (1993) loss module) and that this is easily avoided. If a far too small (very inaccurate) area for a catchment is used, e.g. the nominal catchment area of 2km^2 for the spring at Blewbury (see previous sub-section), IHACRES with the JH (1993) loss module generates $u_k >> r_k$ over large proportions of a model calibration period. As discussed by Littlewood (2020) this is a computational artefact and is easily remedied by using an accurate catchment area. A catchment area of 30 km^2 for Mill Brook at Blewbury solves the problem.

Variants of the JH (1993) loss module have been applied within an IHACRES framework (Littlewood and Post, 1993, 1995; Chen *et al*, 1995; Ye *et al*. 1997). Ye *et al*. (1997) introduce two additional calibrated parameters to the JH (1993) loss module, replacing s_k in Eq. 16 by $(s_k - l)^p$. This additional complexity may be useful for low-yielding catchments with ephemeral streams in harsher climates than experienced in the UK, e.g. parts of Australia, but probably is not needed for relatively high-yielding UK catchments with perennial streams.

Croke and Jakeman (2004) introduce a catchment moisture deficit (CMD) loss module for IHACRES, based on Evans and Jakeman (1998). Croke and Littlewood (2005) apply the CMD loss module in IHACRES to the seven catchments listed earlier in Table 12, comparing results with those obtained using the JH (1993) loss module. For the two largest catchments, the Teme and the Tywi, the CMD loss module gives a better overall model-fit than obtained using the JH (1993) loss module but for the Gwili, Irfon, Cothi, Conwy and Teifi the CMD loss module does not perform as well.

Loss modules that can exploit additional soil moisture measurements have been developed and used on an *ad hoc* basis within IHACRES. A SVAT-UH example outlined earlier in Section 3 (see 'Model Complexity issues') is applied to a 0.65 km^2 Kenyan bamboo-vegetated catchment**.** Robinson and Stam (1995) use soil moisture measurements to develop a simple s-curve-based loss module for the 234 km^2 Ock at Abingdon. They report that, for the Ock, replacing the JH (1993) loss module with an s-curve loss module decreased the length of record required for IHACRES model calibration and improved the model-fit.

4. Engineering hydrology and IHACRES

This Section compares the FSR and IHACRES UHs qualitatively and considers the potential utility of IHACRES for engineering hydrology in the UK, specifically for assisting with the systematic estimation of design hydrographs corresponding to appropriate design rainfall profiles. The design hydrograph may be required for a catchment that is gauged for flow, or it may be needed for an ungauged catchment.

The IHACRES UH has not gained traction for UK engineering hydrology, probably because the FSR UH and a minor variant of it (described later) have occupied seemingly unassailable positions in recommended procedures from 1975 to the time of writing. Since the 1970s, the UK engineering flood hydrology community (engineering hydrologists, researchers who devise and supply the design flood hydrograph techniques for practical use, and relevant Government Departments/Agencies) has invested heavily in the FSR UH-based rainfall–streamflow model and minor variants of it. For this reason alone, perhaps, there is little appetite for substantial changes to the UH element of current design flood hydrograph estimation procedures. There is also an inherent inertia to substantial change (improvement) in the currently recommended package of procedures for design flood hydrograph estimation, as will be discussed later.

Earlier, in Section 1, Table 1 records that the FSR (NERC, 1975) is widely regarded as a key development in UK hydrology. Products of the FSR are methodologies for application by engineering hydrologists to estimate design hydrographs at gauged and ungauged sites throughout the UK. An important specific application of FSR methods is estimation of probable maximum flood (PMF) hydrographs against which the conveyance of reservoir dam spillways can be assessed for their safety[11]. The FSR UH method is part of the procedural guidance given by the Institution of Civil Engineers (ICE, 2015) for statutory inspections of spillways at certain categories of dams in the UK.

As an element of the FSR rainfall–streamflow model the FSR UH is a direct flow UH that is constrained to be a simple triangle defined solely by its time to peak, Tp. (The peak, Qp, and the width of the triangle at its base on the time axis, TB, are prescribed to be simple functions of Tp.) The FSR and a subsequent update of it, i.e. the Flood Estimation Handbook (FEH) (IH, 1999), include statistical relationships between Tp and catchment characteristics, enabling estimation of the triangular UH at ungauged sites. The FEH retained the FSR UH without changes. In sharp contrast to the FSR/FEH UH, the IHACRES UH is for streamflow, as described in Section 2. When, as is often the case, the IHACRES UH is characteristic of quick- and slow-flow acting in parallel it is completely defined by three DRCs ($\tau^{(q)}$, $\tau^{(s)}$, SFI) and has a mixed-exponential recession limb.

[11] In the early 1980s, the author applied the (then) fairly new FSR/ICE method of Probable Maximum Flood (PMF) hydrograph estimation to assist with statutory inspections of dam spillways for several major reservoirs.

> "Additional attractive features of the [IHACRES] methodology are that neither the selection of individual 'suitable' storm events, nor the prior separation of baseflow, are necessary – these are common steps in many other methods of unit hydrograph identification – e.g. the [FSR] method given for systematic UK floods studies …" Littlewood and Jakeman (1991a). (Terms within square brackets have been added for this Paper.)

In 1997, when work was underway towards the FEH, an article appeared in the BHS Newsletter *Circulation* (Archer, 1997) raising issues concerning the FSR rainfall–streamflow modelling method. In the subsequent issue of *Circulation* there are two responses (Reed and Houghton-Carr, 1998; Lowing, 1998). These three articles address points of detail concerning application of FSR methods but do not discuss the FSR triangular UH or mention the IHACRES UH that had been introduced some seven years earlier. A brief article in the next issue of *Circulation* **(**Littlewood, 1998) compares IHACRES and FSR UHs qualitatively. As a contribution to the International Association of Hydrological Sciences (IAHS) Prediction in Ungauged Basins (PUB) Decade (2003-2012), Littlewood (2004) compares the FSR and IHACRES UHs in the context of gauged and ungauged catchments, with a focus on some of the uncertainties involved. (See also Littlewood *et al*. (2007b) for a paper based on a 2002 proposal for an IHACRES component of PUB.)

Lowing (1998) argues that the FSR design flood hydrograph estimation package should be seen and applied

> " … *as a whole*; it simply is not fair to take one element in isolation and highlight its weaknesses. The *combination* of (a) unit hydrograph, (b) percentage runoff, (c) design storm (amount, duration, profile) and (d) baseflow was designed *and calibrated* to match *observed flood frequency curves* on *individual* catchments … Any criticism of the method must recognise this …" (typefaces as per the original).

This persuasive argument (from a Past President of BHS, 1991-1993) warrants inspection and discussion. It is inevitable that elements of any design hydrograph estimation package will be assessed and their weaknesses highlighted, with or without a view towards eventual improvements to the package. Whether or not that is "fair" is difficult to judge. More than 20 years on, it is perhaps increasingly important, if it was not already so in the 1990s, to recognise that the UH element of the FSR design hydrograph package should not remain un-changed for ever in the light of relevant technical advances. Otherwise, inertia can occur (and in this case has). Having said that, the short-to-medium term practicality of Lowing's argument above is sound; for a package where the parts affect each other, one part cannot be changed substantially without an overhaul of the whole thing possibly being required. Furthermore, any procedure that is tinkered with frequently, in response to minor improvements to separate parts of the whole package, runs the risk of becoming unpopular with practitioners and therefore untenable as a national standard.

The long-term credibility of a recommended package that has in-built resistance to advances in techniques related to its parts, or appears to be managed to resist such advances,

can be rather weak. There will come a time when, in the light of substantial advances in techniques and understanding, an unchanged recommended methodology might lose the attractions it once had. The author believes that the IHACRES UH introduced in 1990 is a substantial advance on the FSR/FEH UH, and that the time for a major overhaul of UK design hydrograph estimation procedures has been overdue for some time. It would seem unwise, at least, to not fully investigate the utility for engineering hydrology of the progress that has been made in UH identification since the 1970s.

Qualitative comparisons of IHACRES and FSR UHs, e.g. Littlewood and Jakeman (1991a) and Littlewood (1998), do not suggest that the IHACRES UH could simply replace the triangular UH in the FSR methodology. For the reasons given by Lowing (1998) and discussed above this just would not work: it would not even be a sensible proposition. A substantial change to the UH element of currently recommend procedures would, indeed, require a major overhaul of the whole procedure – a task of some magnitude requiring considerable ingenuity (as was exercised in embedding the FSR rainfall–streamflow model in currently recommended procedures) and one not to be undertaken lightly.

With publication of the FEH in 1999, parts of the FSR design flood hydrograph methodology were improved, e.g. based on analyses of the longer hydrometric datasets that had accrued since the early 1970s. However, as already noted, the FEH retains the FSR triangular UH unaltered. Later, in separate work, a kink was introduced on the recession limb of the FSR UH (Kjeldsen, 2007), leading to the 'revitalised FSR/FEH rainfall–runoff model' (ReFH). It is possible that this kink was introduced in recognition of the success of the mixed-exponential decay UH recessions that IHACRES shows to be so effective for a wide range of catchments in the UK and elsewhere. Like the FSR triangular UH the ReFH kinked-UH is for a poorly defined direct flow component of streamflow. To date, the FSR triangular UH is still recommended as part of estimating design flood hydrographs for assisting with statutory inspections of reservoir spillways for certain categories of UK dams.

The UK engineering hydrology profession specifies design flood hydrograph estimation procedures for application by engineering hydrologists, with the Institution of Civil Engineers (ICE) playing a leading role. For some reservoir dam safety work, relevant UK Government Departments/Agencies ensure compliance. Where, for example, the hydraulic conveyance of a spillway is not adequate to carry an appropriate design flood safely around an earth embankment dam there may be potential grave consequences to consider. Furthermore, remedial engineering work to increase the capacity of an existing spillway can be costly. Decisions by the engineering profession and relevant Government Departments/Agencies concerning what methods to recommend for estimating design flood hydrographs, when to update/change those recommended methods, etc, are crucially important. It is right that such decisions are informed by specialists but not taken by them, and in this sense the British Dam Society (BDS) and BHS, as Specialist Knowledge Societies affiliated to the Institution of Civil Engineers (ICE), have important roles to play.

Faulkner and Benn (2019) present a useful review of UK design flood estimation practice for reservoir hydrology, suggesting ways forward. They identify seven areas where current methods need attention or clarification, one of which is rainfall–streamflow modelling. Their review discusses several aspects of the similar FSR and ReFH rainfall–streamflow models, both of which include an outdated UH for unmeasurable direct flow. Without giving details beyond stating concerns about the capability of the FSR/ReFH UHs for modelling larger-than-recorded floods, the review refers to "limitations" of the unit

hydrograph concept, before suggesting that process-based models using high-resolution digital terrain data may be better suited for reservoir flood estimation. Somewhat curiously, given the long history of UH theory application for modern engineering hydrology, the review fails to consider (or even mention) the possible benefits of IHACRES UHs within a rainfall–streamflow modelling framework for reservoir flood hydrology.

A Government-commissioned review by Balmforth (2021) addresses many important issues related to dam safety that go far beyond the scope of this Paper. Understandably in such a far-reaching review, the Balmforth Report does not consider explicitly the UH basis of design flood hydrograph estimation for spillway flood hydrology and whether or not it is in need of improvement. However, the Report does cover these aspects of dam safety implicitly. Considering the maintenance of competence of reservoir Supervising and Inspecting Engineers, the Report observes that

> "The collective knowledge of any professional area does not stand still. Knowledge grows through experience, *advances in science and technology, research and development* and most importantly from incidents. It is important that reservoir engineers and other personnel continue to develop throughout their professional career by contributing to and learning from the growing body of knowledge in their field" (italics have been added for this Paper).

Previous Sections of this Paper illustrate advances in UH identification and application that may not be sufficiently well known or appreciated by the reservoir engineering hydrology community. Table 13 summarises and compares several features of the FSR and IHACRES UHs that may be of interest to the engineering hydrology profession and relevant Government Departments/Agencies if and when substantial changes to the recommended UH-based procedures for design flood hydrograph estimation are considered. A version of the Table was shown as part of the presentation by the author "Precision and accuracy of Unit Hydrograph parameters for gauged and ungauged basins: Can we do better?" at a joint national meeting of BHS and BDS "UK Reservoir Spillway Flood Hydrology" held at the Institution of Civil Engineers, 7th March 2019.

Table 13: Comparing FSR/FEH and IHACRES UHs

Feature	FSR/FEH triangular UH (engineering hydrology)	IHACRES UH (environmental hydrology)
What flow is modelled?	**Direct flow (non-measurable)**	**Streamflow (measurable)**
High flows modelled?	**Yes**	**Yes**
Low flows modelled?	**No**	**Yes**
Event-based modelling?	**Yes**	**Yes**
Continuous streamflow simulation?	**No**	**Yes**
Prior hyetograph separation required?	**Yes**	**No**[a]
Prior hydrograph separation required?	**Yes**	**No**
Automated hydrograph separation provided?	**No**	**Yes**[b]
Smoothing of UHs identified from hydrometric data required?	**Yes**	**No**
UH parameters transferable to ungauged catchments?	**Yes**	**Yes**

After Littlewood (2008).

The colour-coding facilitates interpretation: **blue** and **red** indicate relatively **good** and **not-so-good** features.

a. Automatically by a parameter grid-search method within model calibration.
b. Dominant quick- and slow- response components of streamflow.

5. IHACRES software

The IHACRES software used by JLW (1990) and for several of the research applications outlined in this Paper was based on FORTRAN code by the first author of JLW (1990). However, it was suitable for use only by those with access to large mainframe computing facilities, e.g. for the work by Sefton and Howarth (1998) mentioned earlier.

During the 1990s, growth in ownership and distribution of personal computers (PCs) occurred at great pace. The IHACRES FORTRAN code was re-structured to work on early PCs as described by Jakeman *et al*. (1991). All aspects of PC computing were advancing rapidly, and the Institute of Hydrology (IH) at Wallingford, with the Centre for Resource and Environmental Studies (CRES) at the Australian National University, Canberra, jointly developed an IHACRES package with a graphical user interface (GUI) for commercial distribution (see Fig. 13). This package, PC-IHACRES, comprised the original IHACRES FORTRAN code within a state-of-the-art GUI shell.



Figure 13: PC-IHACRES 1997

On the basis of a growing list of research publications, PC-IHACRES was marketed for a range of purposes:

- Identification of unit hydrographs
- Continuous time series rainfall–streamflow modelling
- Environmental change and hydrological regime studies
- Runoff event modelling
- Hydrograph separation
- Derivation of a Slow Flow Index (SFI)
- Derivation of Dynamic Response Characteristics (DRCs)
- DRC – Physical Catchment Descriptors (PCDs) relationship research
- Teaching Unit Hydrograph theory and its applications
- Hydrometric data quality assurance/control
- Infilling missing streamflow data.

A comprehensive User Guide (Littlewood *et al*, 1997) describes the functionality of the package and includes tutorials for three catchments in Wales. A thorough independent review of PC-IHACRES (Allen and Liu, 2011) includes scores for PC-IHACRES from 1 (worst) to 5 (best) in four categories: capability (score = 4.7); reliability (4.5); ease-of-use (4.5); and technical support (4.5). In about 2004, administrative changes at IH meant that maintenance of the commercial PC-IHACRES package and Help Desk facilities for it could not be maintained. However, until June 2021 the UK Centre for Hydrology and Ecology (UKCEH) provided PC-IHACRES as a free-to-download package (User Guide included) via its website. Unfortunately, PC-IHACRES does not work with the latest PCs. In July 2021 UKCEH ceased to provide the PC-IHACRES package. Sadly these developments may mark the demise of the PC-IHACRES package for new users and, when our old PCs die, for existing users too, unless a way around the problem can be implemented. Fortunately, however, other free-to-download IHACRES software is available.

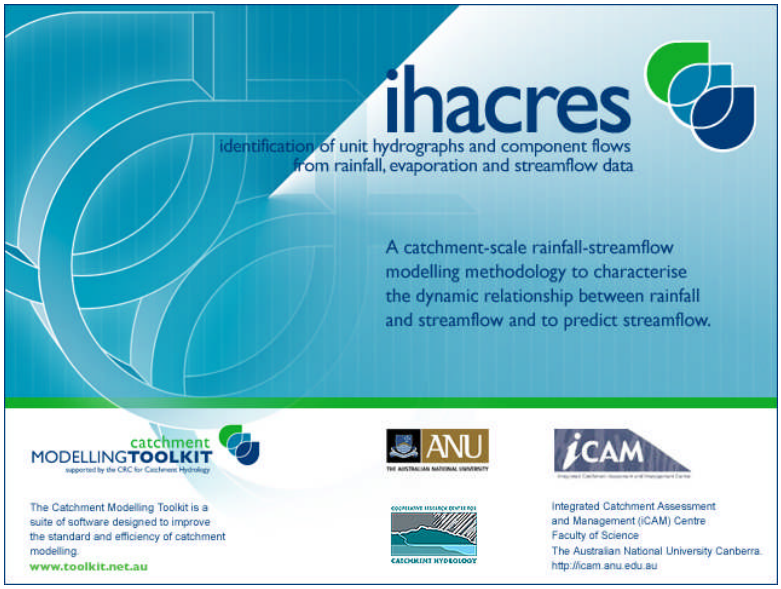


Figure 14: IHACRES v2.0 (Classic Plus)

Croke *et al*. (2005, 2006) introduce a Java-based IHACRES package, to serve as a base on which relevant research developments could be rolled out to a wide user community.

The package is known as IHACRES v2.0 or IHACRES Classic Plus (Fig. 14). IHACRES v2.0 is more powerful than PC-IHACRES (Classic) in several ways, e.g. it has better facilities to assist with selecting a best model. However, whereas PC-IHACRES allows bypassing of the loss module and provides outputs of indicative uncertainties on the UH DRCs, these very useful facilities are not available in IHACRES v2.0. At the time of writing information about IHACRES v2.0 is available from the Australian eWater Toolkit website[12].

Fashions in coding and user-community demands on computer packages have changed, sometimes in a related manner. So-called open coding languages, such as free-to-use R, are increasingly popular with some users. The Hydromad open source facility for hydrological model assessment and development (Andrews *et al.*, 2011) provides an R-code laboratory environment for rainfall–streamflow modelling research and applications (see Fig. 15). Hydromad users can call upon different IHACRES (*m*, *n*) UH module structures, different loss modules and different UH parameter estimation algorithms (including SRIV). Hydromad also allows users to interact with the R code, e.g. to apply a loss module of their choosing. In principle, therefore, Hydromad provides an unprecedented flexibility for those wishing to continue to extend and improve practical aspects of the IHACRES modelling approach. There appears, however, to be a cost in terms of project continuity for some pre-Hydromad IHACRES users. Currently, the Hydromad user wishing to apply or re-calibrate IHACRES models from previous work undertaken using PC-IHACRES or IHACRES v2.0 must have quite a high level of expertise in the R language, whereas users of PC-IHACRES and IHACRES v2.0 do not interact directly with the coding of those packages. On the plus side for Hydromad, the layers of information provided by its website[13] reveal huge potential benefits to those who are already proficient in R or who are prepared to invest in learning that coding skill to the required level. Novices in R can start by working through the very useful tutorials available via the Hydromad website homepage.

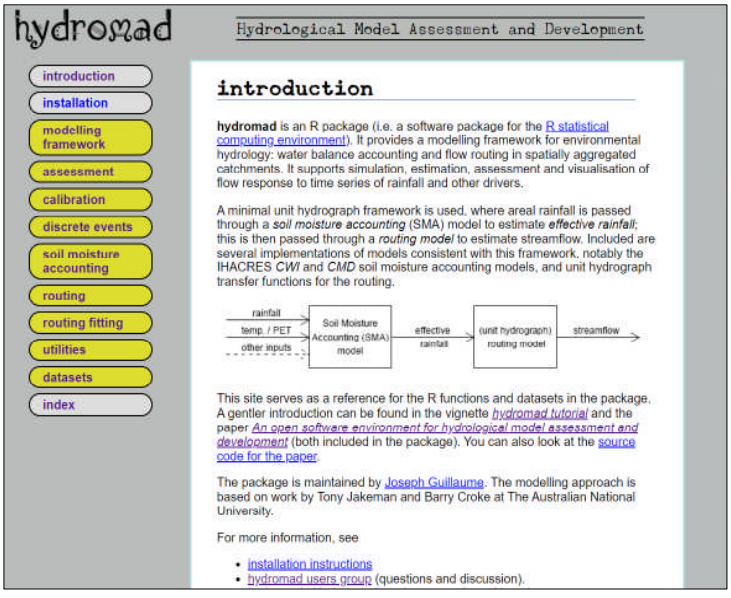


Figure 15: Hydromad website opening page

[12] https://toolkit.ewater.org.au/Tools/IHACRES

[13] http://www.hydromad.catchment.org

6. Concluding remarks

The following concluding remarks reflect upon major points made in previous Sections. The Paper has presented a history of the IHACRES rainfall–streamflow modelling methodology illustrated with summaries of several of its published applications for water resources and environmental hydrology. The Paper has also discussed the potential of the IHACRES UH for engineering hydrology applications, for which a demonstrably inferior type of UH has played a key role in the UK for more than 45 years.

An IHACRES UH is characteristic of (measurable) streamflow, which is a key advantage over UHs for a poorly defined (unmeasurable) direct flow component of streamflow, as currently employed for UK engineering hydrology. The IHACRES model structure is simple but flexible, allowing investigation and selection of a structural complexity in the UH module that is justifiable from information in the hydroclimatological data employed for model calibration. In terms of a coefficient of determination, D, and an average precision on the UH parameters, ARPE, a 3-parameter UH module is optimal for a wide range of catchment types; a larger number of UH parameters can be prescribed for a given catchment but this is often accompanied by a sharp decrease in their average precision. In which case the additional parameter(s) are perhaps not significantly different from zero and can be omitted from the model without noticeably affecting model-fit. Furthermore, the 3-parameter IHACRES UH is the addition of separate UHs for dominant quick- and slow-response components of streamflow acting in parallel, giving hydrograph separation as a product of IHACRES modelling, rather than it being a necessary pre-requisite as in earlier UH identification methods. As described in Section 2, a key feature of IHACRES is the ability of the SRIV algorithm to identify dominant quick- and slow-flow components of the streamflow simultaneously; other IV methods can identify only a dominant quick component of streamflow.

A 6-parameter IHACRES rainfall–streamflow model structure that includes the 3-parameter JH (1993) loss module can give good model fits for widely different catchment types: e.g. the 490 m^2 Hydrohill artificial catchment in China (6-minute interval data); the 34,414 km^2 R. Ivaí at Novo Porto Taquara and other catchments in Brazil (daily data); many catchments in the UK ranging from less than 1km^2 (hourly data) to a little under 10,000 km^2 (daily or monthly data according to size and modelling purpose); and many other catchments around the world. However, this ability to model rainfall–streamflow behaviour over orders of magnitude of catchment size and data timestep, in different hydroclimatic zones, needs to be seen in the context of several modelling issues that the IHACRES user should bear in mind, some of which have been discussed in Section 3 of the Paper.

There is a difference between fitting a model to data and fitting a model to a catchment, as follows. The main concern when fitting a model to data is obtaining a good match between observed and modelled hydrographs, e.g. for flow data infilling. In this case it is good (but not essential) to have calibrated model parameters that have reasonable values

given their conceptual meanings. However, when fitting a model to a catchment an additional concern is that the values of the calibrated model parameters are consistent, like-for-like, with the values of parameters for the same model structure calibrated for other catchments, e.g. as required for model regionalisation.

Inconsistency between the values of a given DRC calibrated for different catchments can arise for other reasons. The sub-section on 'Data timestep issues' in Section 3 discusses how, when the data timestep is too coarse to capture the quick-flow dynamics of the Wye at Cefn Brwyn, massive inaccuracy occurs in the quick flow decay time constant, $\tau^{(q)}$, even though it is estimated with very good precision. The other DRCs are similarly affected but to a lesser extent. For model regionalisation towards estimation of streamflow for ungauged basins it can be important to normalise DRCs to a data timestep of zero, e.g. to obtain an instantaneous UH (IUH). This is an issue that has been neglected in regionalisation studies using IHACRES, and other rainfall–streamflow models, in the UK and other countries.

Another issue when like-for-like consistency in DRCs is required is that bias in the slow flow decay time constant, $\tau^{(s)}$, can occur for some catchments when an IHACRES model is calibrated using only a trade-off between D and ARPE. The sub-section 'Multi-objective model-fitting' in Section 3 includes discussion of how the additional trial-and-error matching of flow-duration curves (FDCs) for observed and modelled streamflow, while varying f in the JH (1993) loss module, can help to correct for the bias in $\tau^{(s)}$ that might arise from models selected using just D and ARPE.

Invoking the sensitivity test of an X% change in rainfall (a crude climate change scenario), the JH (1993) loss module within an IHACRES framework has been correctly criticised. Given a 10% increase in the rainfall input to a model calibrated from hydroclimatic data the result is an unrealistic uniform 21% increase in modelled streamflow for any catchment (a 19% decrease in streamflow for a 10% decrease in rainfall). Although this criticism is valid and requires attention (see later), pragmatically it needs to be seen in a wider context. First, an X% step-change increase or decrease in rainfall is itself totally unrealistic and will never happen (so it is not interesting hydrologically). Second, even for only a slightly more realistic (but still very simplistic) change in rainfall that might be specified by a proposed climate change scenario, e.g. a set of different seasonal or monthly percentage rainfall increases and decreases giving an overall X% change in annual rainfall, the JH (1993) loss module does not generate a uniform percentage change in streamflow for all catchments (see 'Climate change' under 'Environmental change' in Section 3). With due care and attention, therefore, IHACRES including the JH (1993) loss module can be used to estimate indicative changes in streamflow corresponding to simple climate change scenarios. Better climate change scenarios (increasingly more realistic) should give better estimates of changes in streamflow. Other loss modules have been developed for use within an IHACRES framework (see 'Loss modules in IHACRES in Section 3), some of which should be more robust for climate change work but as far as is known their efficacy for that purpose has yet to be fully investigated.

There is no application of UH theory for UK engineering hydrology of greater importance than estimating flood hydrographs (driven by appropriate design rainfall profiles) to assist with checking the adequacy of reservoir dam spillways for safely conveying large floods downstream, especially given the ageing population of UK earth embankment dams with clay cores. Section 4, 'Engineering hydrology and IHACRES', discussed current practice based on the simplistic FSR/FEH triangular or ReFH kinked-triangular UHs, which are for an unmeasurable direct flow component of streamflow. Section 4 also considered the potential utility for engineering hydrology of the IHACRES UH, which is for total streamflow and has several other advantages. Recent reviews of dam safety provisions in the UK, and of recommended engineering hydrology procedures associated with UK reservoir

spillway safety inspections, have not considered explicitly the details of the UH-based rainfall–streamflow model used for such work. Whether the advances in UH identification and application described in this Paper (and elsewhere previously) mean that currently recommended reservoir design flood hydrograph procedures are outdated, and in need of substantial reform, does not appear to be being openly considered. Indeed, it is not clear from recent relevant publications (see Section 4) that the UK engineering hydrology community is sufficiently aware that such advances have been made or, therefore, of the implications of this for the credibility of currently recommended procedures based on the FSR UH introduced more than 45 years ago.

The Paper has focused on two types of UH-based rainfall–streamflow modelling, mainly IHACRES (UHs for total streamflow and its dominant quick and slow components) but also the FSR/FEH/ReFH method (direct flow UHs). Of course, many other rainfall–streamflow modelling approaches exist. It remains to be seen what models and methodologies eventually replace the FSR/FEH/ReFH UH models and methods for UK engineering hydrology. As mentioned in Section 4, it has been suggested by others that process-based models using high-resolution digital terrain data may be better suited for reservoir spillway flood hydrology than the current UH-based method (FSR/FEH/ReFH). This may well prove to be the case but it does not encourage parallel consideration and assessment of other modelling approaches, e.g. using advances in the application of UH theory. It is suggested, therefore, that a range of modelling options for flood hydrograph estimation should be considered and evaluated towards improving UK engineering hydrology. In this context there are two broad attractions of the IHACRES approach. First, for modelling catchment-scale rainfall–streamflow dynamic behaviour, structurally simple IHACRES rainfall–streamflow models can perform at least as well as structurally detailed process-based models, where the latter tend to be far more costly in terms of their data and computing requirements. Second, the IHACRES approach is based on UH theory already familiar to UK engineering flood hydrologists.

Acknowledgements

There has been continual Australia–UK collaboration for the development and application of IHACRES (including software packages), from the late 1980s to date. As this Paper has recorded, the JLW (1990) paper was just the start of an ongoing series of many IHACRES-related publications, only some of which have been summarised and discussed in this Paper. Without the SRIV technique the IHACRES project may not have started. Working with Tony Jakeman (ANU), especially in the early months and years of IHACRES, has been a pleasure and an inspiration.

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Any errors in the Paper are solely those of the author. Views and opinions expressed do not necessarily reflect BHS policy.

Glossary

ARPE	average relative parameter error
BDS	British Dam Society
BFI	base flow index
BHS	British Hydrological Society
BIV	basic instrumental variable
CMD	catchment moisture deficit
D	a coefficient of determination
DRC	dynamic response characteristic
EC	electrical conductivity
FDC	flow duration curve
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
GCM	global circulation model
GUI	graphical user interface
IAHS	International Association of Hydrological Sciences
ICE	Institution of Civil Engineers
IHACRES	Identification of Unit Hydrographs And Component flows from Rainfall, Evaporation and Steamflow data
IUH	Instantaneous Unit Hydrograph
JH (1993)	Jakeman and Hornberger (1993)
JLW (1990)	Jakeman, Littlewood and Whitehead (1990)
LS	Least squares
MGB	Modelo de Grandes Bacias
NRFA	National River Flow Archive (UK)
PCD	physical catchment descriptor
PC-IHACRES	the IHACRES software package for personal computers
ReFH	the revitalised FSR/FEH rainfall – runoff method
SFI	slow flow index
SRIV	simple refined instrumental variable
SVAT	soil-vegetation-atmosphere transfer
UH	Unit Hydrograph

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