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Characterization of flow regimes for three French rivers using a 6-parameter continuous simulation rainfall–streamflow model: the importance of the parameter selection procedure

IAN G. LITTLEWOOD

Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, UK

igl@ceh.ac.uk

Abstract An established 6-parameter rainfall–streamflow modelling package (PC-IHACRES) is applied to three French catchments using daily data sets made available to participants of a Model Parameter Estimation Experiment (MOPEX) workshop held in Paris, 2004. For one catchment, Le Loupe at Villeneuve-Loubet, the main aim is to characterize the flow regime over as wide a range of flows as possible, using a single set of model parameters selected by a multi-objective model parameter selection procedure. Using a more restricted, twin-objective, parameter selection procedure, a subsidiary aim for each of the three catchments (additionally Le Guillec at Trézilidé and Le Toulourenc at Malaucène), is to investigate how well a model calibrated on a sub-period of the available record performs on a different sub-period not used for model calibration. For Le Loupe at Villeneuve-Loubet, the 6-parameter model structure, with a single set of parameters calibrated over almost the entire available record, characterizes the flow regime between 5 percentile and 80 percentile flows. Split-sample analyses for Le Guillec at Trézilidé and Le Loupe at Villeneuve-Loubet, using two sub-periods of the available record in each case, demonstrate the difficulty of capturing a time-invariant characteristic response for those two catchments. A similar split-sample analysis suggests that Le Toulourenc at Malaucène has an essentially time-invariant characteristic response to rainfall. The results are discussed in the context of similar analyses reported in the literature, and with respect to the potential of the 6-parameter model for some aspects of regionalizing model parameters against physical catchment descriptors to enable flow simulation at ungauged sites.

Key words flow regime characterization; rainfall–streamflow modelling; regionalization; ungauged catchments

INTRODUCTION

In the late 1980s and early 1990s, computational advances in the application of unit hydrograph (UH) theory were marked by the development of the IHACRES approach to rainfall–streamflow modelling (e.g. Jakeman *et al*, 1990; Littlewood & Jakeman, 1994; Littlewood *et al.* 1997) (IHACRES: Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data). For the first time, it became possible to systematically identify UHs for total streamflow (not a poorly-definable "direct flow" component of streamflow) from continuous records of rainfall and flow (not just "runoff event" data sets). Furthermore, the need was removed for prior separation of a baseflow component of streamflow, as is common in modelling approaches that identify a UH for "direct" flow only. Rather, the new methodology allows hydrograph separation as an integral part of the procedure, to give dominant quick- and slow-response components of streamflow.

The paper applies PC-IHACRES to characterize the rainfall–streamflow dynamics of three French catchments (43, 150 and 279 km^2), using data provided to participants of a Model Parameter Estimation Experiment (MOPEX) workshop held in Paris, 2004.

The model and modelling package

While a UH for total flow can be represented by one of a number of configurations of linear stores acting in parallel and/or series, the optimal configuration identifiable from information in commonly available rainfall and streamflow time series is usually two linear stores in parallel. These two linear stores generate dominant quick- and slow-response components of modelled streamflow (e.g. Littlewood & Jakeman, 1992). Typically, the IHACRES loss and UH modules each have three parameters (i.e. the whole model has just six parameters). Given its parametric parsimony, the potential for establishing statistical relationships between IHACRES model parameters and physical catchment descriptors has been recognized, investigated and commented upon by several researchers (e.g. Jakeman *et al.* 1992; Littlewood & Jakeman, 1994; Post & Jakeman, 1996, 1999; Sefton & Howarth, 1998; Littlewood, 2002, 2003; Kokkonen *et al.* 2003).

The PC-IHACRES modelling package (Littlewood *et al.*, 1997) applied in this paper incorporates the loss model structure introduced by Jakeman & Hornberger (1993). Equations (1) to (9) in Tables 1 and 2 define the model where: r_k, u_k, s_k, Q_k and t_k are respectively rainfall (mm), effective rainfall (mm), catchment wetness index (-), streamflow (mm) and air temperature (ºC) at time-step k (in this paper $k = 1$ day); τ_w is a catchment drying time constant (days); f is a temperature modulation factor (ºC^{-1}); R is a reference temperature (in this paper $R = 20$ºC); C (mm^{-1}) is selected to give a water balance between the volumes of effective rain and observed streamflow over the model calibration period; $a_1^{(q)}$, $a_1^{(s)}$, $b_0^{(q)}$, $b_0^{(s)}$, a_1, a_2, b_0, and b_1 are coefficients of linear UH transfer functions; z^{-1} is the backward shift operator, i.e. $z^{-1}x_t = x_{t-1}$; and δ is a pure time delay (for all three catchments $\delta = 0$ days was found to give better models than $\delta = 1, 2, \ldots$ days). Equation (5) is the second-order transfer function representation of the two first-order transfer functions in equation (4).

Table 1 The IHACRES model.

Loss module		UH module	
$u_k = r_k \dfrac{(s_k + s_{k-1})}{2}$	(1)	$Q_k = \left[\left(\dfrac{b_0^{(q)}}{1 + a_1^{(q)} z^{-1}}\right) + \left(\dfrac{b_0^{(s)}}{1 + a_1^{(s)} z^{-1}}\right)\right] u_{k-\delta}$	(4)
$s_0 = 0$			
$s_k = Cr_k + \left(1 - \dfrac{1}{\tau_w(t_k)}\right) s_{k-1}$	(2)	$Q_k = \left(\dfrac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}}\right) u_{k-\delta}$	(5)
$\tau_w(t_k) > 1$			
$\tau_w(t_k) = \tau_w \exp(f(R - t_k))$	(3)		

Table 2 Unit hydrograph dynamic response characteristics (DRCs).

DRC	Quick flow		Slow flow	
Characteristic decay response times for data time step Δ, e.g. 1 day	$\tau^{(q)} = \dfrac{-\Delta}{\ln(-a_1^{(q)})}$	(6)	$\tau^{(s)} = \dfrac{-\Delta}{\ln(-a_1^{(s)})}$	(7)
Relative volumetric throughflow, where $V = \dfrac{b_0^{(q)}}{1+a_1^{(q)}} + \dfrac{b_0^{(s)}}{1+a_1^{(s)}}$	$\nu^{(q)} = \left(\dfrac{b_0^{(q)}}{1+a_1^{(q)}}\right)\left(\dfrac{1}{V}\right)$	(8)	$\nu^{(s)} = \left(\dfrac{b_0^{(s)}}{1+a_1^{(s)}}\right)\left(\dfrac{1}{V}\right)$	(9)

Preliminary selection of a set of parameters giving a best model fit can be made through a trade-off between a high coefficient of determination (D) and a small average relative parameter error ($ARPE$) for UH module parameters a_1, a_2, b_0, and b_1, as fully described elsewhere (e.g. Jakeman *et al.*, 1990; Littlewood *et al.*, 1997). The statistics D and $ARPE$ are defined by equations (10) and (11). In equations (10) and (11): Q_o is observed flow; Q_m is modelled flow; and the σ terms are standard deviations on the UH module parameters as indicated by subscripts (the UH parameter estimation algorithm employed in IHACRES yields a variance-covariance matrix for a_1, a_2, b_0, and b_1). For one catchment, as will be seen later, the twin-objective (D, $ARPE$) procedure was extended by subsequent trial-and-error adjustment of loss module parameter f in search of an improved match between the low-flow sections of flow duration curves for observed and modelled flows.

$$D = 1 - \frac{\Sigma(Q_o - Q_m)^2}{\Sigma(Q_o - \overline{Q}_o)^2} \tag{10}$$

$$ARPE = \left[\left(\frac{\sigma_{a_1}}{a_1}\right)^2 + \left(\frac{\sigma_{a_2}}{a_2}\right)^2 + \left(\frac{\sigma_{b_0}}{b_0}\right)^2 + \left(\frac{\sigma_{b_1}}{b_1}\right)^2\right] / 4 \tag{11}$$

The data

One option offered to MOPEX2004 workshop participants was to analyse daily data, 1 August 1995–31 July 2002, for the three catchments listed (with basic details) in Table 3.

Table 3 Basic catchments details.

Catchment	Code	Area (km^2)	Mean annual		Runoff (%)	Mean air temp. (°C)	Gaps in record?
			precip (mm)	runoff (mm)			
Le Guillec à Trézilidé	J3024010	43	1029 [a]	550 [a]	53 [a]	11.6	no
Le Toulourenc à Malaucène	V6035010	150	1115 [b]	354 [b]	32 [b]	9.2	yes
Le Loup à Villeneuve-Loubet	Y5615030	279	1043 [c]	511 [c]	49 [c]	11.8	yes

[a] 1996–2001; [b] 1999–2001; [c] 1997–2001.

Apart from the time series of daily rainfall, streamflow and air temperature, measurement units and basin areas, no other information about the catchments was known to the author at the time of analysis. Hereafter, the catchments will be referred to using the identification codes given in Table 3, rather than the names of the rivers and the sites at which they are gauged.

RESULTS

Catchment Y5615030

Model Y1 for Y5615030 was calibrated over the longest period of unbroken flow record (3 September 1996–31 July 2002), and has $D = 0.836$ and $ARPE = 0.01$. The model-fit is shown in Fig. 1. For flows less than approximately the 20 percentile, model Y1 tends to overestimate flow increasingly with decreasing flow. As reported elsewhere (Littlewood, 2002, 2003), similar overestimation of low flows by *D*-*ARPE* trade-off PC-IHACRES models has been noted for several catchments in Wales and, in some cases, alleviated by subsequent manual fine-tuning of loss module parameter f as outlined above.

Figure 2 shows the effect of manual fine-tuning of parameter f for Y5615030, to give model Y4. (Models Y2 and Y3, not reported here, were intermediate; it is convenient to retain reference to models Y1 and Y4.) Table 4 gives the parameters of models Y1 and Y4, and their values of D and $ARPE$. Ideally, both f and τ_w should have been varied, but given the limited time available for analysis, parameter τ_w for model Y1 (9 days) was held constant while parameter f was varied to find model Y4. Model Y1 has the higher D, and supports the finding and comment by Wagener *et al.* (2004), made in the context of an investigation of several different, parametrically parsimonious, model structures, that "*A distinct difference in optimum parameter sets to fit high and low flows was found for all structures analysed ... This seems to be the*

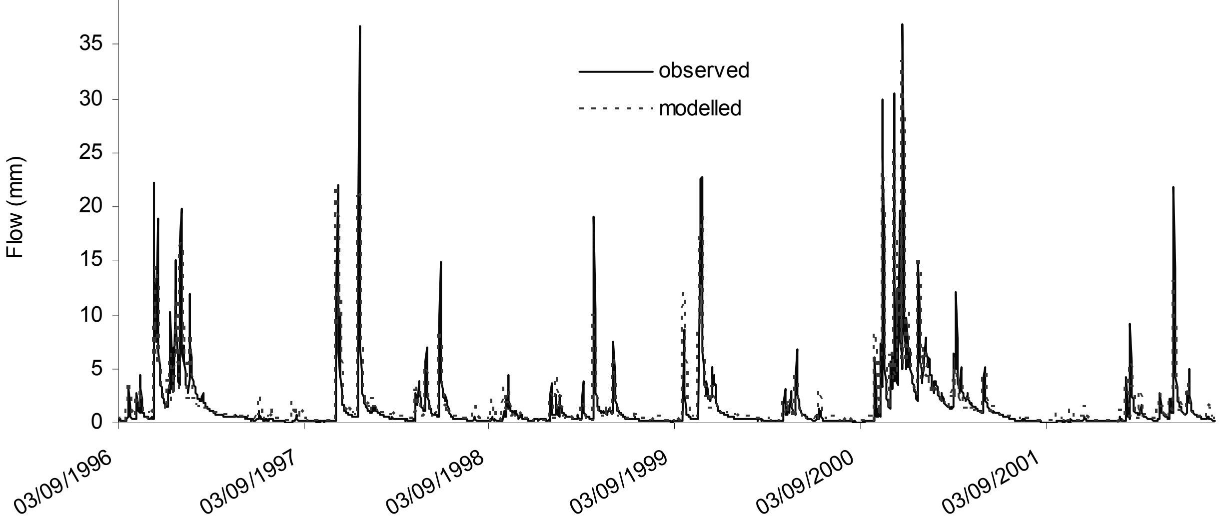

Fig. 1 Catchment Y561030 model Y1 3 September 1996 to 31 July 2002.

Table 4 Catchment Y5615030 models Y1 and Y4.

Model	D	$ARPE$	f ($^{o}C^{-1}$)	τ_w (days)	$1/C$ (mm)	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	$v^{(s)}$ (–)
Y1	0.836	0.01	0.0558	9	227	2.8	75	0.40
Y4	0.790	0.02	0.155	9	416	3.4	110	0.20

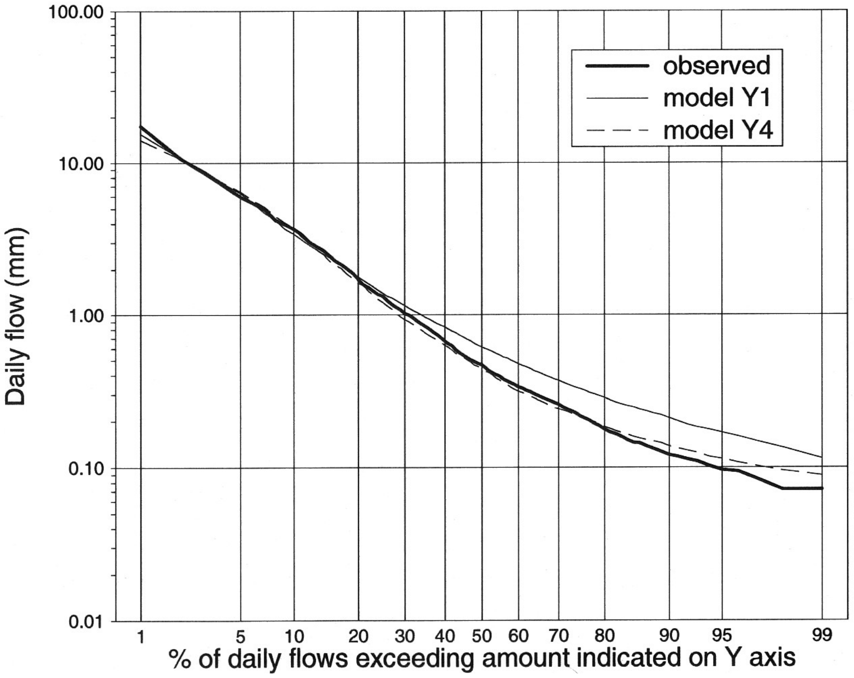

Fig. 2 Catchment Y5615030 flow duration plots 3 September 1996 to 31 July 2002.

main problem in currently available CRR model structures." (CRR: "catchment rainfall–runoff".) However, by accepting small reductions in: (a) D (recalling that maximizing D favours model-fit at high flows over model-fit at lower flows) and (b) the average precision on the UH parameters (i.e. an increase in $ARPE$), it can be seen in Fig. 2 that model Y4 extends the range of flows over which a given model structure performs well with a single set of six parameters. The region of overestimation is reduced from flows less than the 20 percentile (model Y1) to flows less than the 80 percentile (model Y4). In five out of seven catchments in Wales (129 km^2 to 1480 km^2), Littlewood (2003) fine-tuned parameter f in the same way, leading to good matches between observed and modelled flow duration curves (daily data) over even larger portions of the flow range, i.e. between the 5 percentile and 95 percentile (between the 1 percentile and 99 percentile in some cases).

All three catchments

Reverting to the restricted D-$ARPE$ trade-off method of parameter selection for each catchment, models were calibrated over a sub-period of the available record (period

P1) and then applied to simulate flows over a sub-period not used for calibration (period P2). A model was then calibrated over period P2 and run in simulation mode over period P1.

Tables 5 and 6 show the results. Each of the six calibrated models accounts for 80%, or more, of the initial variance in observed streamflow. For V6035010, there is little difference between *D* for the calibration and simulation periods, suggesting that a good characterization of the rainfall–streamflow dynamics for that catchment would be obtained by calibrating a model over the whole available record.

Table 5 Split-sample analyses.

Catchment	Sub-period			*D*	*ARPE*
J3024010	20 Aug. 95–2 Sep. 1998	P1	C	0.796	0.16
	3 Sep. 1998–30 Jul. 2002	P2	S	0.805	–
	3 Sep. 1998–30 Jul. 2002	P2	C	0.865	0.07
	20 Aug. 1995–2 Sep. 1998	P1	S	0.670	–
V6035010	13 Nov. 1995–12 Oct. 1998	P1	C	0.803	0.04
	14 Nov. 1998–29 Jul. 2002	P2	S	0.802	–
	14 Nov. 1998–29 Jul. 2002	P2	C	0.804	0.04
	13 Nov. 1995–12 Oct. 1998	P1	S	0.794	–
Y5615030	3 Sep. 1996–13 Aug. 1999	P1	C	0.809	0.04
	14 Aug. 1999–31 Jul. 2002	P2	S	0.833	–
	14 Aug. 1999–31 Jul. 2002	P2	C	0.863	0.02
	3 Sep. 1996–13 Aug. 1999	P1	S	0.785	–

P1, sub-period 1; P2, sub-period 2; C, calibration period; S, simulation period.

Table 6 Split-sample analysis model parameters.

Catchment		τ_w (days)	*f* (°C^{-1})	1/*C* (mm)	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	$v^{(s)}$ (–)
J3024010	P1	22	0.0620	241.0	1.68	50.4	0.802
	P2	10	0.0744	142.5	1.83	44.9	0.697
		(–54)	(20)	(–41)	(9)	(–11)	(0.105)
V6035010	P1	4	0.155	382.4	3.85	45.1	0.254
	P2	3	0.170	356.1	4.08	32.2	0.299
		(–25)	(10)	(–7)	(6)	(–29)	(0.045)
Y5615030	P1	13	0.0620	276.9	3.00	59.5	0.345
	P2	7	0.0558	201.4	2.62	80.9	0.445
		(–46)	(10)	(–27)	(–13)	(36)	(0.100)

P1, P2 – see Table 5.
Numbers in parentheses are percentage changes between P1 and P2 (absolute change for $v^{(s)}$).

However, for both J3024010 and Y561030, the model calibrated over the earlier of the two sub-periods performs better in simulation mode (in terms of *D*) over the later sub-period than it does over its calibration sub-period. Furthermore, the model calibrated over the later of the two sub-periods performs worse in simulation mode over the earlier sub-period. Correspondingly, some of the model parameters for each of J3024010 and Y561030 are quite different for the two sub-periods, suggesting that characterization of the flow regime has not been achieved as successfully (in terms of *D* and *ARPE*) for these two catchments as for V6035010.

DISCUSSION

IHACRES models calibrated using a multi-objective parameter selection procedure involving fine-tuning of parameter *f* for Y5615030, and for several Welsh catchments (Littlewood, 2002, 2003), give improved characterization of the low-flow portion of flow regimes, albeit with varying degrees of success. Further work is certainly required to assess the full potential of "whole flow regime" modelling using simple models like IHACRES. However, wide ranges of flow, including fairly high and low flows, can be modelled with a single set of six parameters, at least for some catchments and provided that a suitable, multi-objective, parameter selection procedure is followed. Where the objective is to establish statistical relationships between model parameters and physical catchment descriptors, to allow flow simulation at ungauged sites from inputs of rainfall and air temperature, it is important to ensure that the model performs well over as wide a range of flows as possible. Thus $\tau^{(q)}$ and $\tau^{(s)}$, for example, will be more likely to exhibit useful correlations with the physical catchment descriptors that may control the dominant quick- and slow-response components of streamflow.

It should always be remembered that the very lowest and highest flows for a given catchment, especially at and near the peaks of large floods, are typically more difficult to measure accurately than flows that occur more often. Partly for this reason, the very highest flows may require different modelling approaches. Furthermore, flows at and near hydrograph peaks are often not well defined by discrete daily time-step data; analysis of sub-daily data by the IHACRES method may help to model these high flows. However, as the data time-step decreases, or as catchment size increases, the spatial variance of rainfall within a cathment tends to increase. In either case a point will be reached when it is unreasonable to expect a spatially lumped model to perform well, and the catchment will need to be considered as several sub-catchments.

The split-sample analyses presented for all three catchments gave two types of result. For V6035010, models calibrated on either sub-period have about the same *D* and perform well in simulation mode on the other sub-period. The split-sample models for V6035010 have fairly similar model parameters, indicating that a good, time-invariant, characterization of the rainfall–streamflow dynamics exists for that catchment. For the other two catchments, although as good (or better) models, in terms of *D*, to those obtained for V6035010 were calibrated on one of the sub-periods, time-invariant characterization was not so successful. As shown in Table 6, for τ_w, *f*, $1/C$, $\tau^{(q)}$ and $\tau^{(s)}$ the percentage changes (absolute change for $v^{(s)}$) between periods P1 and P2 are less (or, in one case, the same) for V6035010 than for J3024010 and Y5615030. Catchments J3024010 and Y5615030 are perhaps more complex hydrologically than V6035010, such that time-invariant characteristic responses do not exist. If they do have time-invariant characteristic responses, it is possible that split-sample models calibrated using additional fine-tuning of parameter *f* (and τ_w), seeking a good match between flow duration curves for observed and modelled flows as an additional modelling objective, would give better models for J3024010 and Y5615030. Further analysis is required to investigate these points, using any additional time series that might exist for the catchments but were not available for the MOPEX workshop.

CONCLUDING REMARKS

This short paper has demonstrated the utility of PC-IHACRES for quickly analysing rainfall–streamflow dynamics at catchment-scale. Although the author was not familiar with the catchments, reasonably good model-fits were obtained in terms of D and, additionally in the case of Y5615030, a match between low-flow portions of flow duration curves for observed and modelled flows. Knowledge about the catchments and their hydrometry could have been useful; it is, of course, recommended that such information is used whenever possible.

While some modellers consider that different model structures, or different parameter sets for the same model structure, are required to model low and high flows at a given site, work presented here and elsewhere suggests that that is not always the case at daily time-step, provided that the very lowest or highest flows are not the main focus of interest. For a given model structure, the parameter calibration and selection procedure can be crucially important, especially when the modelling objective is to characterize catchment rainfall–streamflow behaviour, e.g. for model regionalization via relationships between model parameters and physical catchment descriptors to allow estimation of flow at ungauged sites from rainfall and air temperature (Littlewood *et al*., 2002).

Rainfall–streamflow model parameters selected solely on the basis of D (the well-known Nash-Sutcliffe efficiency) are not good enough, especially for helping to devise regionalization schemes for predicting flow in ungauged catchments. This paper has demonstrated that a multi-objective modelling approach is essential for such work. Given the limitations of PC-IHACRES as a package, the additional use of flow duration curves, as described in the paper and elsewhere (Littlewood, 2002, 2003), requires considerable manual effort combined with assessment of flow duration curves "by eye". This hybrid, automatic-manual approach to parameter selection has the strong positive feature that it keeps the hydrologist closely involved in the modelling exercise, "*combining the strengths of manual and automatic methods*" (Boyle *et al*., 2000). In order to facilitate the calibration of models for hundreds, or even thousands, of catchments, as required for systematic regionalization, it will be necessary to automate suitable multi-objective parameter selection procedures. Future rainfall–streamflow modelling software could incorporate the matching of flow duration curves for observed and modelled flows as an additional objective. While this is a useful goal, and probably will happen, manual aspects of model calibration should never be under-valued.

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