

PROGRESS WITH UNIT HYDROGRAPH-BASED RAINFALL–STREAMFLOW MODELS FOR ENGINEERING AND ENVIRONMENTAL HYDROLOGY

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Introduction

This short paper compares two rainfall–streamflow modelling approaches used for engineering and environmental hydrology applications respectively. In each case the model comprises a module to estimate effective rainfall followed by a unit hydrograph module. Statistical relationships between the models' parameters and catchment attributes have assisted with modelling streamflow at ungauged sites. For more than 30 years, since 1975, the first modelling approach has been used extensively in the UK for systematic, flood event, engineering hydrology, e.g. design flood estimation. The prototype of the second approach, which can model continuous hydrographs over several seasons or years (and over single events), was introduced in 1990 and has been applied mainly for environmental hydrology. Variants of the model structure in the second approach have been applied for investigating the impacts of environmental change (e.g. land-use, climate) on streamflow regimes. The second modelling methodology represents substantial progress in the application of UHs for environmental hydrology and could also be useful for engineering hydrology.

The first rainfall–streamflow modelling approach is described in the Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) and its forerunner the Flood Studies Report (FSR) (NERC, 1975), and will be referred to subsequently as the FSR/FEH rainfall–streamflow method. The second modelling approach is IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data), first introduced by Jakeman *et al.* (1990). For details of the modelling approaches, their applications, and further discussion of many of the points raised in this short paper, the reader is invited to consult Littlewood (2008) and references therein.

An example is presented of IHACRES model parameter sensitivity to the time-step of the data used for model calibration. Similar information is presented for a baseflow index (BFI), comparing it with a slow flow index (SFI) generated by IHACRES. The implications of these results for model parameter regionalisation studies are discussed.

Comparing the FSR/FEH and IHACRES methods

The FSR/FEH unit hydrograph (UH) represents a direct flow component of streamflow. The reader is reminded that there is no known method of measuring direct flow. Direct flow for an event is estimated by an intuitively reasonable, though somewhat arbitrary, hydrograph separation. Similarly, effective rainfall for the event in question is estimated by an intuitively reasonable hydrograph separation method. A UH

Table 1 Summary comparison of FSR/FEH and IHACRES rainfall–streamflow modelling methods

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 ¹ ✓
Prior hydrograph separation required?	Yes ✗	No ✓
Automated hydrograph separation provided?	No ✗	Yes ² ✓
Smoothing of UHs identified from hydrometric data required? ³	Yes ✗	No ✓
UH parameters transferable to ungauged catchments?	Yes ✓	Yes ✓
1. Automatically by a parameter grid-search method within IHACRES model calibration. 2. Dominant quick- and slow-flow response components of streamflow. 3. Using the matrix inversion method stated in the FSR.		

is then identified from the effective rainfall and direct flow. Several events are thus analysed and an average UH computed. To estimate the hydrograph for a different event the relevant hyetograph is first separated to give effective rainfall, which is then convolved with the average UH to generate direct flow for the event, to which is added an appropriate baseflow. The FSR/FEH method is not suitable for modelling hydrographs continuously over seasons or years.

The IHACRES unit hydrograph represents total streamflow, thereby circumventing the problem of having to estimate a rather poorly defined direct flow component prior to UH identification. Hydrograph separation, giving dominant quick- and slow-response components of modelled streamflow, is a by-product of the methodology. IHACRES can model hydrographs continuously over seasons and years (as well as over single events). There are several variants of IHACRES model structure.

Table 1 summarises various features of the FSR/FEH and IHACRES rainfall–streamflow modelling methods. Comparison of the features in Table 1 supports the argument that IHACRES represents an advance in the application of UH theory that has been exploited for environmental hydrology and could, in principle, be exploited additionally for engineering hydrology. Littlewood (2008) compares FSR/FEH and IHACRES unit hydrographs for an event from a 20 km² catchment in Scotland. Although the FSR/FEH method has been re-designed and improved recently (Kjeldsen, 2007) it still uses a direct flow UH and remains unsuitable for continuous streamflow simulation over several seasons or years.

Regionalisation and model parameter sensitivity to data time-step

An IHACRES model structure that has been used for regionalisation has six dynamic response characteristics (DRCs), which for this paper are called model parameters: a catchment drying time constant, τ_w ; a temperature modulation factor, f ; the depth of a catchment wetness store, c ; a quick-flow decay time constant, $\tau^{(q)}$; a slow-flow decay time constant, $\tau^{(s)}$; and the proportional volumetric contribution of slow-flow to streamflow, $\tau^{(s)}$. The latter DRC is a slow flow index (SFI) that will be referred to again later.

Moderate success has been achieved in relating IHACRES model parameters (and the parameters of other rainfall–streamflow models) to catchment attributes, e.g. Sefton and Howarth (1998), Post and Jakeman (1999), Young (2006), Merz and Blöschl (2004). Merz *et al.* (2006) discuss several reasons for the “... relatively low correlations between model parameters and catchment attributes” but not model parameter sensitivity to data time-step. Indeed this source of uncertainty, which is likely to be important in some regionalisation schemes, appears to have been largely overlooked in the rainfall–streamflow modelling literature until quite recently.

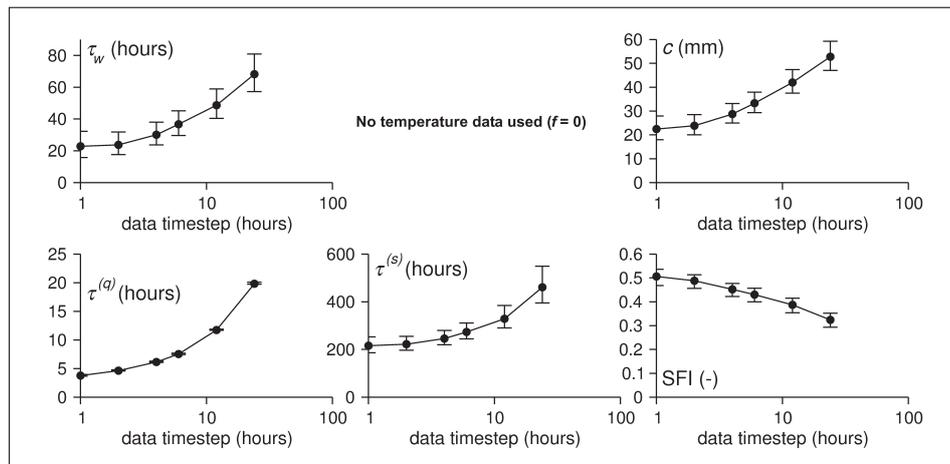


Figure 1. Wye at Cefn Brwyn DRCs against data time-step: model calibration 6 December 1987 – 2 July 1988 (Littlewood and Croke, 2008)

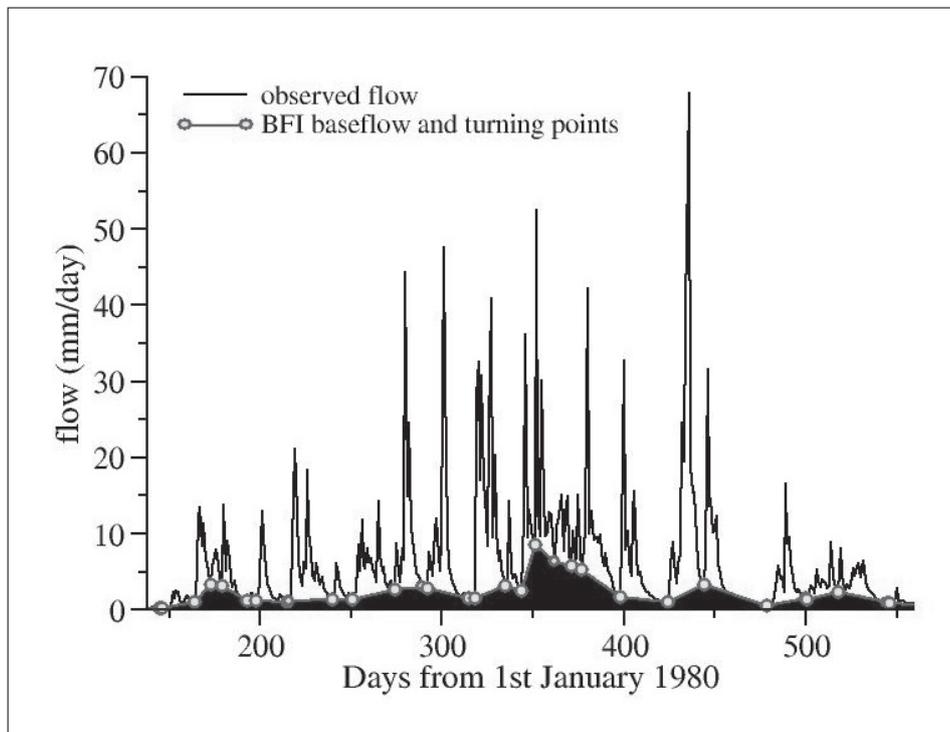


Figure 2. BFI hydrograph separation for the Wye at Cefn Brwyn (daily data) (Littlewood, 2008)

Littlewood (2007) and Littlewood and Croke (2008) demonstrate the extent to which IHACRES model parameters are dependent on the time-step of the data employed for model calibration. Figure 1 shows how each of the IHACRES model parameters for the 10.6 km² Wye at Cefn Brwyn appears to reach or approach a stable value, i.e. insensitive to data time-step, as data time-step decreases to 1 hour. The indicative 95% confidence bands shown in Fig. 1 indicate that precision on the model parameters improves as data time-step decreases from 24 hours to 1 hour. In Fig. 1, the value of a parameter calibrated using 1-hourly data provides a benchmark, and the difference between that benchmark and the same parameter calibrated using n -hourly data can be considered to be a measure of the accuracy associated with that n -hourly parameter. Precision and accuracy thus have quite different meanings. The uncertainty associated with a model parameter is a combination of its precision and accuracy.

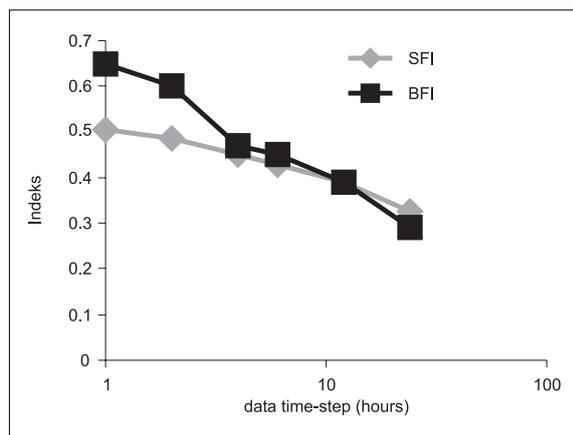


Figure 3. Wye at Cefn Brwyn (a) BFIs using different data time-steps (b) SFIs and BFIs 6 December 1987 to 2 July 1988 (Littlewood, 2008)

It is anticipated that the parameters of other discrete-time rainfall–streamflow models will also exhibit sensitivity to data time-step. When such models are calibrated for many gauged catchments using a common data time-step (e.g. daily), and their parameters are subsequently linked to catchment attributes (regionalisation), a proportion of the uncertainty in the resultant statistical relationships will be due to a common time-step having been used. An alternative modelling approach, which could be useful for regionalisation studies, is the continuous-time data-based mechanistic (DBM) approach introduced by Young and Romanowicz (2004) and Young and Garnier (2006). Continuous-time DBM models yield model parameters that should be insensitive to data time-step. Such model parameters should exhibit superior statistical relationships with physical catchment descriptors to those from discrete-time models, and therefore lead to a reduction in uncertainty associated with streamflow estimates at ungauged sites.

There is a pressing need to assess the parameter data time-step sensitivity of rainfall–streamflow models that have been, or could be, used to assist with streamflow estimation at ungauged sites. The paper now considers an example. Although the Gustard *et al.* (1992) baseflow index (BFI) is not the output from a rainfall–streamflow model (it is derived solely from streamflow data) it can be considered to have model parameters, and it is interesting to assess its sensitivity to those parameters and data time-step. BFI is a key catchment statistic in floods and low-flow regionalisation studies in the UK and has also been applied for studies in Canada, Fiji, Zimbabwe, New Zealand and Norway (Gustard *et al.*, 1992). Period-of-record BFIs derived from daily mean streamflow records are published for more than 1000 UK catchments as “...a measure of the proportion of the river runoff that derives from stored sources” (NERC, 2003).

In outline, BFI is usually computed from daily flows, as follows. The minimum flow in each consecutive, non-overlapping, block of five flows ($Q_1, Q_2, \dots, Q_5; Q_6, Q_7, \dots, Q_{10};$ etc.) is identified. The block minima, in overlapping groups of three consecutive values, are then inspected using simple rules to decide if the middle value of each group is a baseflow turning point. An unbroken sequence of daily baseflow values is estimated by interpolating between pairs of consecutive baseflow turning points. Interpolated daily baseflows can occasionally be greater than the corresponding observed streamflows, in which case they are adjusted to the observed streamflows. The area under the adjusted baseflow hydrograph is expressed as a proportion of the area under the observed streamflow hydrograph to give the baseflow index ($0 < \text{BFI} < 1$). The BFI algorithm can be considered to include two parameters: the length of non-overlapping flows (L) and a multiplicative factor (F) that is applied to ensure identification of sensible baseflow turning points. Usually, L is 5 (as above) and F is 0.9. Using daily data, values of L and F other than 5 and 0.9 respectively will return different values of BFI for a given catchment. The BFI hydrograph separation ($L=5, F=0.9$) over a short period of the daily record for the Wye at Cefn Brwyn is shown in Fig. 2, where the shaded area represents the separated adjusted baseflow.

The IHACRES hydrograph separation that gives dominant quick- and slow-response components of modelled streamflow yields a slow flow index (SFI) analogous to BFI. Figure 3 shows how BFI and SFI for the Wye at Cefn Brwyn change as the data time-step varies between 1 hour and 24 hours. While SFI changes by about 18 percentage points, BFI changes by about 36 percentage points, i.e. BFI is twice as sensitive to data time-step as SFI. Furthermore, while SFI shows signs of approaching a stable value at small data time-steps there is no indication of this happening for BFI.

Summary and concluding remarks

There is seldom information available with which to assess the accuracy of rainfall–streamflow model parameters, though their precision can often be assessed using statistical methods. However, IHACRES model

parameters for the Wye at Cefn Brwyn calibrated using hourly data (Fig. 1) provide a reasonable benchmark against which the accuracy of parameters calibrated using other data time-steps can be assessed. The uncertainty associated with a model parameter is a combination of accuracy and precision.

The Wye at Cefn Brwyn case illustrates how model parameters estimated with good precision can be inaccurate, and therefore have large uncertainty. For example, in the lower left panel of Fig. 1 values of $\tau^{(q)}$ estimated using daily and hourly data are about 20 hours and 4 hours respectively, both with good precision. So, although $\tau^{(q)}$ (daily data) is estimated with good precision it is very inaccurate, i.e. about +400% of the benchmark estimated using hourly data, and therefore it has very high uncertainty. The other parameters shown in Fig. 1 are not estimated with precisions as good as that for $\tau^{(q)}$ but they are inaccurate too, though at +190% (τ_w), +132% (c), +110% ($\tau^{(s)}$) and -18 percentage points (SFI) not to the same degree as $\tau^{(q)}$.

From the results presented for IHACRES and BFI it appears likely that the parameters of many, perhaps all, discrete-time rainfall–streamflow models are sensitive to data time-step, unless specific adjustments are made to account for this modelling artefact. Parameters estimated with poor precision may effectively hide the inaccuracy of some model parameters.

Adopting a given data time-step for modelling a set of gauged catchments possessing a range of dynamic responses will account for some of the uncertainty associated with parameter regionalisation equations developed subsequently. The proportion of this uncertainty might be quite high in some cases. Further work is required to investigate and quantify the magnitude of this regionalisation modelling issue.

Much interesting research remains to be undertaken. The PUB¹ Top-Down modelling Working Group (TDWG) provides one forum for researchers interested in rainfall–streamflow modelling and information transfer to ungauged basins. For details of the TDWG and TRUMPER (Towards Reducing Uncertainty in rainfall–streamflow Model Parameter Regionalisation) the reader is invited to visit <http://tdwg.catchment.org/>.

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¹ The Prediction in Ungauged Basins Decade (2003-2012) of the International Association of Hydrological Sciences

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