Comparison Of Alternative Loss Modules In The IHACRES Model: An Application To 7 Catchments In Wales

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EXTENDED ABSTRACT

The IHACRES model has been successfully applied to many catchments across the UK including regionalization studies (e.g. Sefton and Howarth, 1998; Littlewood, 2003). However, while the previous formulation of the non-linear module performs well in calibration and simulation, the module has some identified deficiencies in the representation of the impacts of climate change on volume of streamflow. The recently developed Catchment Moisture Deficit (CMD) version of the non-linear module (Croke and Jakeman, 2004) has a stronger physical basis than the previous formulation of the IHACRES non-linear loss module, which potentially enhances the performance in regionalization studies.

The ultimate aim of this study is to apply the model to 60 catchments in England and Wales and examine potential regionalization strategies using the CMD model. The previous IHACRES model has already been applied to a regionalization study based on these catchments, and a comparison of the two results will be used to evaluate the strengths and weaknesses of the two versions of IHACRES for such studies.

This paper describes initial tests on the performance of the revised IHACRES model on 7 catchments in Wales. The catchments span a range of areas from 129 to 1480 km^2 with most having a high runoff coefficient of greater than 0.7, with the remaining catchment located in east Wales, and has a runoff coefficient of 0.44 (Littlewood, 2003).

Using cross correlation analysis, one of the 7 catchments (Teme) was found to have no seasonality in the rainfall distribution and only a slight seasonality in the streamflow response. In comparison the remaining 6 catchments all had strong seasonal variation in the streamflow driven by a slight seasonality in the rainfall. In addition, all 6 catchments had very similar streamflow-rainfall cross correlation functions, indicating that a similar model structure should apply to all 6 catchments, and that there is a strong potential for regionalization.

Based on deconvolution of the cross correlation functions, the delay between rainfall and the peak of the catchment response function is between 0 and 1 days. The centre of gravity of the response function is a measure of both the delay in the peak as well as the rate of decay from the peak, and has a significant correlation with catchment area.

The CMD version of the IHACRES gave better performance than the non-linear module of Jakeman and Hornberger (1993) for the Teme catchment (R_{NS}^2 = 0.70 compared with 0.65 found by Littlewood, 2003). However, for five of the remaining six catchments, the CMD module performed slightly worse than the previous version of the module. While the number of catchments included in this study is too small to provide a conclusive analysis of the performance of the CMD module, the results suggest that the CMD module performs better than the previous version on larger catchments.

1. INTRODUCTION

In order to predict flows at ungauged sites using calibrated rainfall-runoff models, a method of estimating a parameter set is needed. A number of techniques (e.g. Merz and Blöschl, 2004) have been employed including:

- Determining regression relationships between model parameter values and catchment attributes
- Adopting a parameter set from a nearby, catchment that is expected to have sufficiently similar response characteristics
- Interpolation schemes (e.g. kriging) of parameter values from nearby catchments

Methods based on estimating parameter sets rather than individual parameter values have a considerable advantage due to the highly non-linear nature of catchment responses and the correlations that typically exist in rainfall-runoff models (Croke and Norton, 2004). Thus, application of regression relationships between catchment attributes and individual parameters requires parsimonious models that have strong relationships between parameters and catchment attributes as well as little correlation between different parameters. While IHACRES (Jakeman, *et al.*, 1990) has been used in previous regionalisation studies (e.g. Post and Jakeman 1996 and 1999, Post et al. 1998, Sefton and Howarth 1998, and Kokkonen et al. 2003), the CMD version of the non-linear loss module has a potentially better structure for regionalization. This paper compares the performance of the CMD module with that of the previous non-linear loss module (Jakeman and Hornberger, 1993).

2. STUDY CATCHMENTS

The catchments included in this study are shown in Figure 1, and some basic catchment details are given in Table 1 (BFI = Base Flow Index defined by Gustard et al., 1992). These catchments were included in the set of 60 catchments used by Sefton and Howarth (1998) in a regionalization study for catchments in England and Wales. Littlewood (2003) improved the model calibrations for the catchments listed in Table 1, referring to sets of results from the procedure adopted by Sefton and Howarth (1998) as 'Set A' and from an extended calibration procedure as 'Set B'. Calibration of Set B models involved manual tuning of one of the model parameters to improve the match between the low-flow sections of flow duration curves for observed and modeled flows; only Set A results are referred to in the current paper. This paper compares models that include the CMD non-linear module to Set A models that use the Jakeman and Hornberger (1993) non-linear module.

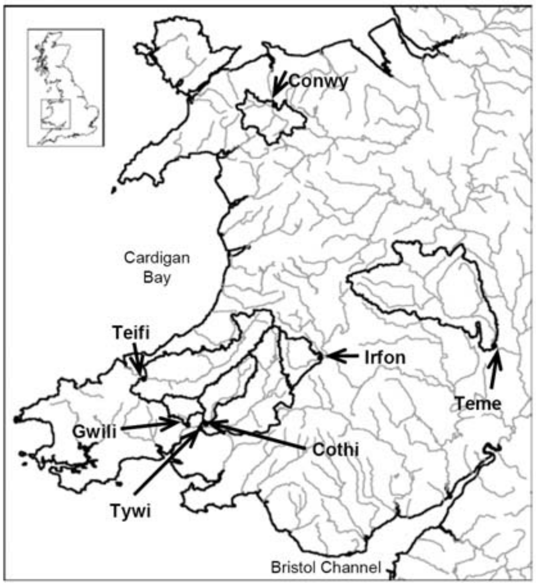

Figure 1. Study catchments, with arrows indicating the location of the gauging sites (from Littlewood, 2003).

3. DATA ANALYSIS

Figure 2 shows the flow and rainfall cumulative frequency distributions for the Teifi catchment. Based on daily data, this suggests that the flow duration curve is determined by the rainfall frequency distribution for days with rainfall greater than about 100mm (exceedence fraction of 0.06). Further, for these high rainfall days (assuming the antecedent flows are relatively low), approximately 50% of the rainfall is converted into streamflow within a single timestep (1 day in this case) after the lag between rainfall and streamflow is allowed for (1 day for the Teifi). It should be noted that such extreme events are unlikely to be represented well by IHACRES unless the calibration period includes an adequate number of these events.

Table 1. Catchment details

Catchment	Gauge	Area	Mean rainfall	Mean runoff	Runoff	BFI
		km^2	mm/yr	mm/yr	coeff.	
Gwili at Glangwili	60006	129	1628	1180	0.72	0.46
Irfon at Cilmery	55012	244	1673	1275	0.76	0.39
Cothi at Felin Mynachdy	60002	298	1645	1191	0.72	0.43
Conwy at Cwm Llanerch	66011	344	2189	1688	0.77	0.28
Teifi at Glan Teifi	62001	894	1355	997	0.74	0.54
Tywi at Nantgaredig	60010	1090	1574	1107	0.70	0.46
Teme at Knightsford Bridge	54029	1480	828	366	0.44	0.57

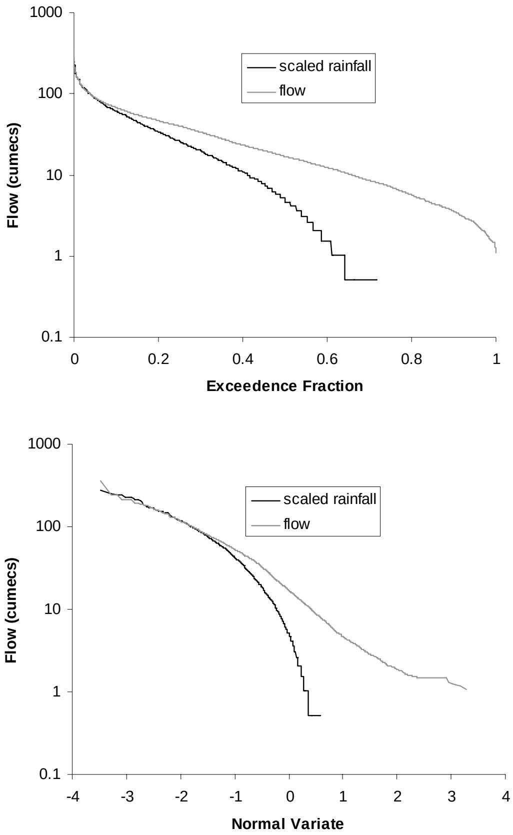

Figure 2. Flow duration curve for the Teifi catchment. The rainfall exceedence curve is also presented, with the rainfall converted into cumecs, and multiplied by 0.5.

3.1. Cross correlation

Based on a cross correlation analysis (Croke, 2005), the 7 catchments fall into two groups. The six smallest catchments show evidence of a slight seasonality in the rainfall distribution, and a stronger seasonality in the streamflow (see Figure 3). The remaining catchment (Teme) does not show evidence of seasonality in the rainfall distribution, and only marginal evidence for the streamflow distribution (see Figure 4). This suggests that there may be significant differences in model parameter sets, or even in appropriate model structures required to model these groups of catchments. For the six smallest catchments, the cross correlation of streamflow with rainfall yields very similar functions, with the Conwy catchment having considerably higher noise.

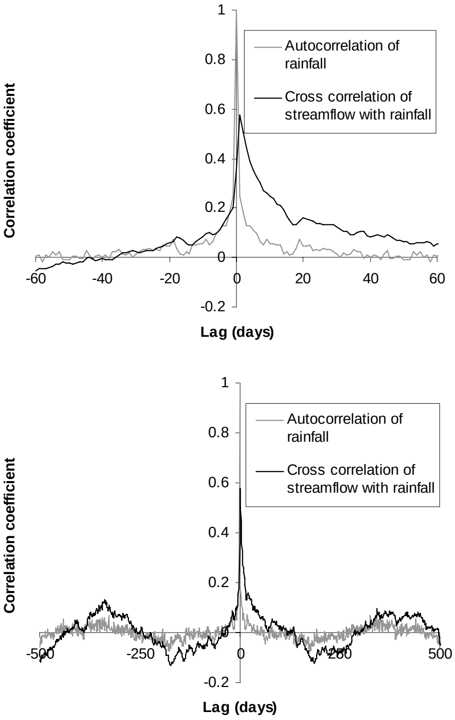

Figure 3. Cross correlation analysis for the Teifi catchment. The top panel shows the influence of the catchment response, while the bottom plot shows the seasonality present in the data.

The top panels in Figures 3 and 4 show the peak of the correlation functions. The peak value in the cross correlation of streamflow with rainfall depends on the data quality, the degree to which the rainfall represents the effective rainfall as well as the peakiness of the catchment response function.

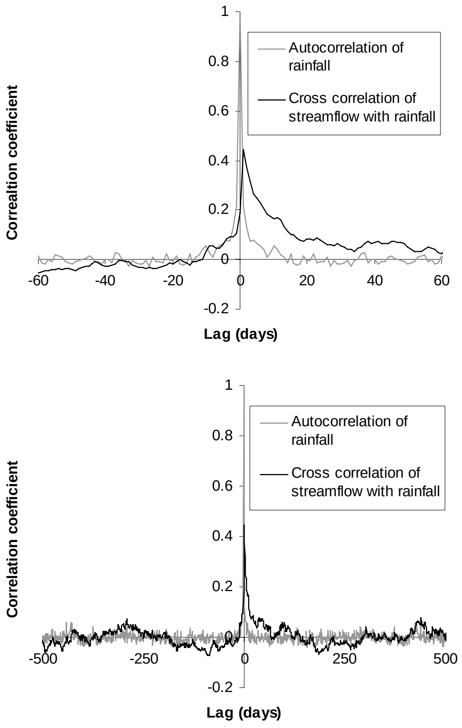

Figure 4. Cross correlation analysis for the Teme catchment. The top panel shows the influence of the catchment response, while the bottom plot shows the seasonality present in the data.

3.2. Deconvolution

The cross correlation function also shows the influence of the catchment response function. Assuming that the auto-correlation of rainfall is sufficiently similar to the auto-correlation of effective rainfall, the unit hydrograph (UH) can be estimated using a deconvolution approach (Croke, 2005). Figure 5 shows the resulting catchment response function for the Teme catchment, and shows a 1 day lag between rainfall and streamflow response, though there is a small, but still significant response at lag=0 suggesting that the delay is slightly less than 1 day (c.f. Littlewood (2003) where a value of 0.8 was found). Further, the recession from the peak of the response function is relatively slow, suggesting the quick flow time constant is considerably greater than 1 day (based on daily data).

The centre of gravity (CoG) of the resulting response function was derived for each catchment, and gives an indication of the delay between rainfall and streamflow (combined with the width of the response function). This is presented as a function of catchment area in Figure 6, along with the peak of the cross correlation function (CCP). There is a clear trend for CoG to increase with increasing area, but with considerable scatter (due to other contributing factors such as topography and channel morphology). Ideally, the CoG should tend to zero as the catchment area tends to zero. However, the use of daily data will tend to artificially increase the CoG for small catchments. As a result, the linear fit to the data gives a non-zero intercept. Consequently, a power law form has been adopted, even though the resulting R^2 is less. Similarly, there is a slight tendency for the CCP value to decrease with increasing area due to the influence of a broadened UH, though any effect of area is almost completely masked by the scatter.

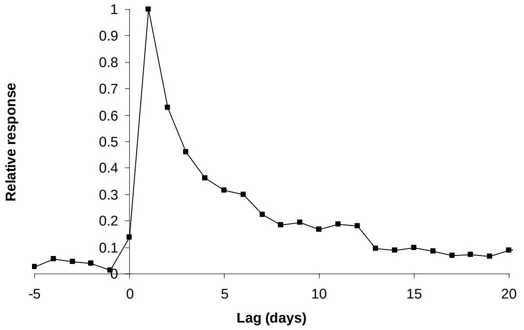

Figure 5. Deconvolved catchment response function for the Teme catchment (normalised to the peak of the response function).

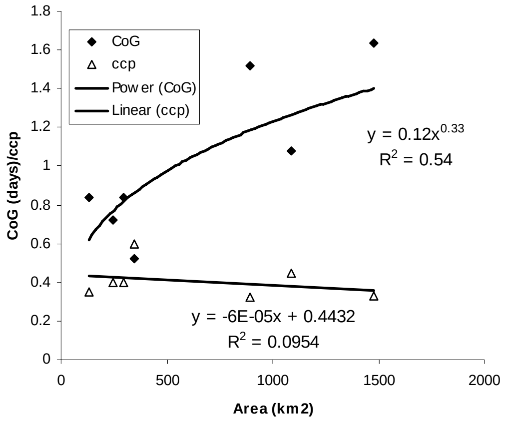

Figure 6. Dependence of the centre of gravity (CoG) and peak of the cross correlation function (CCP) on catchment area

4. IHACRES CMD MODULE

The CMD module has been described by Croke and Jakeman (2004). The CMD module has a stronger physical basis than the PC-IHACRES non-linear module and hence is potentially a better model for regionalization studies.

The module has two components. The first component determines the fraction of rainfall in the current timestep that will become streamflow. The second component estimates the evaporative loss in each timestep, and therefore determines the antecedent conditions for each rainfall event. While the model has been extensively tested on Australian catchments, little work has been done in other countries.

The module has three calibrated parameters: *d* (flow threshold), *e* (coefficient to convert temperature into potential evaporation) and *f* (stress threshold parameter). An additional two parameters determining the shape of the discharge relationship were fixed at values suggested by Croke and Jakeman (2004).

5. APPLICATION OF THE CMD MODEL

To aid in the comparison of the performance of the non-linear modules, the linear module parameters for set A in Littlewood (2003) were adopted. The CMD module parameter values for each catchment are given in Table 2.

Table 2. Calibrated CMD module parameter values

Catchment	*d*	*e*	*f*
Gwili	10	0.25	1.74
Irfon	10	0.25	4.0
Cothi	10	0.25	2.96
Conwy	15	0.25	2.9
Teifi	30	0.15	1.48
Tywi	70	0.35	1.02
Teme	90	0.25	0.6

6. COMPARISON WITH PREVIOUS WORK

Table 3 gives the Nash Sutcliffe model efficient (R_{NS}^2) and bias values for set A of Littlewood (2003) and this study. The CMD performs significantly better for the Teme, and generally worse on the remaining 6 catchments (the exception is the Tywi, which is the largest of the remaining catchments). Figure 7 shows the variation in the relative performance of the CMD module (measured as the difference in R_{NS}^2 between the results here and the set A results from Littlewood, 2003) with catchment area. There is a clear trend in the results for better relative performance of the CMD module with increasing catchment area (albeit for a small sample of catchments).

Table 3. Comparison with Set A of Littlewood (2003).

Catchment	Set A		This study	
	R_{NS}^2	bias	R_{NS}^2	bias
Gwili	0.806	-3.99	0.746	4.02
Irfon	0.751	0.25	0.694	12.23
Cothi	0.777	-3.26	0.767	3.92
Conwy	0.778	0.19	0.761	5.17
Teifi	0.836	-4.39	0.832	-0.18
Tywi	0.759	-4.23	0.786	0.58
Teme	0.638	-3.60	0.700	0.00

(Note: bias in given as a percentage of flow)

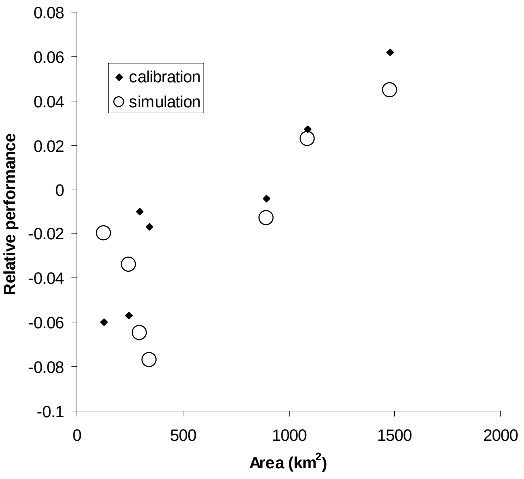

Figure 7. Relative performance of the CMD module.

Examples of the FDCs derived using the parameter values for set A of Littlewood (2003) and those for the CMD model are given in Figures 8 and 9. The under-estimation of the high flows for the Irfon is likely to be the result of using the linear module parameters from set A. The quick-flow time constant t_q was generally higher for set A than set B in the analysis presented by Littlewood (2003). However, the decline in the flow peaks suggests that the CMD form is underestimating the flood peaks compared with the previous non-linear loss module.

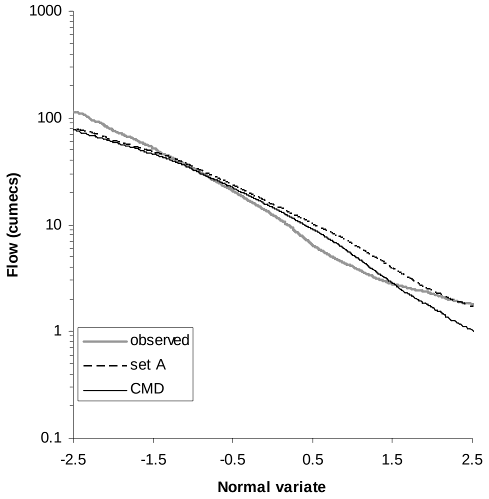

Figure 8. Observed and modeled flow duration curve for the Teme catchment

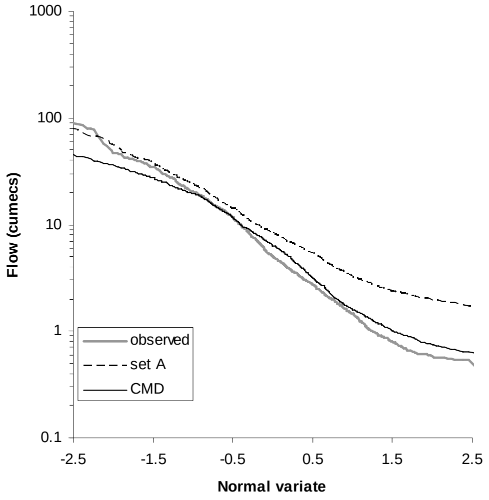

Figure 9. Observed and modeled flow duration curve for the Irfon catchment

7. CONCLUSIONS

A key component of the top-down approach to modelling is evaluating and comparing model structures to identify strengths and weaknesses. This can lead to potential improvements in model structures, as well as determining where particular model structures perform best.

Based on this study of 7 catchments in Wales, the CMD version of the IHACRES non-linear module tentatively appears to perform better than the previous model for catchments greater than 1000km^2. This is based on a small sample, and more extensive testing will be required to confirm this.

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