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Unit Hydrographs and Regionalisation of United Kingdom River Flows: Comments on Some Estimation Uncertainties

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Abstract: Two types of unit hydrograph (UH) are discussed, with an emphasis on uncertainties. The paper reviews the 1-parameter triangular unit hydrograph (UH) employed to assist with systematic design flood hydrograph estimation for ungauged United Kingdom catchments. A 6-parameter rainfall-runoff model that incorporates a 3-parameter UH is also discussed. The precision and accuracy of characteristic decay times for dominant quick and slow response UHs, derived from the 6-parameter model, are examined in the context of uncertainty in flow regime regionalisation. On the basis that, as argued in the paper, the full potential of the 3-parameter UH has yet to be exploited for regionalisation of flow regimes, there are plans for further work along these lines during the International Association of Hydrological Sciences (IAHS) Prediction in Ungauged Basins (PUB) Decade (2003-2012).

Keywords: Unit hydrographs; Regionalisation; Flow regimes; Uncertainties

1. INTRODUCTION

The unit hydrograph (UH) has, for many decades, been a major component of rainfall-runoff modelling for systematic flood hydrology in the UK and elsewhere. Based on procedures introduced in the Flood Studies Report (FSR) [NERC, 1975], the UK's Flood Estimation Handbook (FEH) [Institute of Hydrology, 1999] presents a method for estimating simple triangular UHs for gauged catchments. Since the height and base-width of the triangle are constrained to be simple functions of its time to peak, *Tp*, the triangular UH is a 1-parameter model. Employing a statistical relationship between *Tp* and catchment characteristics, the triangular UH can be applied in regionalisation mode for catchments ungauged for flow. A flood event hydrograph at the ungauged site is estimated by convolving the UH (estimated from catchment characteristics) with effective rainfall derived from an appropriate rainfall profile using a separate loss module, followed by the addition of a baseflow hydrograph also estimated separately. The triangular UH is widely employed for flood hydrology.

For hydrological analysis of lower flows, or for characterising whole flow regimes, the 1-parameter triangular UH is, not surprisingly, limited by its conceptual simplicity (e.g. hydrograph recessions are not characteristically linear). Furthermore, the triangular UH, which deals only with a poorly defined direct runoff component of streamflow (an intuitively reasonable baseflow is separated from total streamflow before identification of the UH), is suitable only for application over runoff events. However, the 3-parameter mixed exponential decay UH introduced by Jakeman *et al*. [1990] is characteristic of total streamflow and can simulate continuous streamflow from effective rainfall.

The 3-parameter UH, when placed in series with a simple 3-parameter loss module to create a 6-parameter rainfall-runoff model, has been shown to work well on a wide range of catchments [e.g. Jakeman *et al*., 1993a,b; Littlewood and Marsh, 1996; Post *et al*., 1998; Steel *et al*., 1999; Kokkonen *et al*., 2003]. Regionalisation can be undertaken via statistical relationships between each of the six model parameters in turn (as the dependent variable) and catchment characteristics (as independent variables). The 3-parameter mixed-exponential decay UH does not require prior baseflow separation. Indeed, a hydrograph separation giving dominant quick and slow response components of streamflow is often a by-product of the method [e.g. Littlewood, 2002a]. The 6-parameter rainfall-runoff model referred to here requires only streamflow, rainfall and air temperature data; apart from catchment size no other data, or information about the catchment, is required.

The paper further describes the triangular and mixed-exponential UH approaches, with particular emphasis on some of the estimation uncertainties involved. Although the mixed exponential UH approach can model high flows well at daily time-step on a wide range of catchments, its suitability and potential for assisting with systematic flood hydrology in the UK is not discussed here. Calver *et al*. [2004] outline some of the recent UK research on continuous flow simulation for design flood hydrology purposes.

The International Association of Hydrological Sciences (IAHS) has initiated the Prediction in Ungauged Basins (PUB) Decade (2003-2012). An important overall objective of PUB is to reduce predictive uncertainty. Amongst wide-ranging aims and objectives, the PUB Science and Implementation Plan[1] has two linked modelling targets: Target 1 is to improve existing models; and Target 2 is to develop new innovative models. The work presented in this paper is a contribution to Target 1, with scope for exchanges of ideas with those more engaged in Target 2. The work is representative of the top-down modelling approach which, as one of several investigative approaches that will be applied during the PUB Decade, is considered to have good strategic potential [Young *et al*., 1997; Young, 2002; Littlewood *et al*., 2003; Sivapalan *et al*., 2003].

2. THE TRIANGULAR UH

Equations (1) and (2) are regionalisation equations for the time to peak of the triangular instantaneous UH, $Tp(0)$, published as reviews of the FSR method were undertaken, models were re-worked and, for the FEH (2), advantage taken of the more recent availability of catchment characteristics derived from digital datasets rather than from conventional maps [Institute of Hydrology, 1985; 1999]. In (1) and (2), *S1085*, *MSL* and *DPSBAR* are catchment or stream slope factors, $SAAR_{4170}$ is mean annual precipitation (1941-1970), $URBAN_{FSR}$ and *URBEXT* are indices of the extent of urbanisation in the catchment, *PROPWET* is the proportion of time the catchment is wet, and *DPLBAR* is a mean stream length [NERC, 1975; Institute of Hydrology, 1999]. Equation (1), was derived using data from 175 catchments, and the stated factorial standard error (*fse*) associated with $Tp(0)$ is 1.48, i.e. +48%/-32%. Equation (2), was derived using data from 204 catchments and the stated *fse* is 1.85 [Institute of Hydrology, 1999], i.e. +85%/-54%.

$$Tp(0) = 283\,(S1085)^{-0.33}(SAAR_{4170})^{-0.54}(MSL)^{0.23}(1+URBAN_{FSR})^{-2.2} \qquad (1)$$

$$Tp(0) = 4.270\,(DPSBAR)^{-0.35}(PROPWET)^{-0.80}(DPLBAR)^{0.54}(1+URBEXT)^{-5.77} \qquad (2)$$

On the basis of the published values of *fse* it appears, superficially at least, that the precision with which $Tp(0)$ could be estimated from catchment characteristics worsened between 1985 and 1999. This, however, would be a rash conclusion. The larger number of catchments used to derive (2) might have been expected to lead to a smaller *fse* but may have included a larger proportion of 'difficult' catchments than those used to derive (1). Furthermore, *fse* gives an incomplete assessment of the quality of (1) and (2): the uncertainty associated with particular estimates of $Tp(0)$ using (1) or (2) is conditional on the values of the catchment characteristics for the basin in question. It is not, as suggested by *fse*, the same for all catchments. Nevertheless, the comparison of (1) and (2) highlights the fact that it has not been demonstrated that (2) is better than (1). It is not clear that the catchment characteristics (independent variables) used for (2) are better than those used for (1). A way forward might be to compare (a) the uncertainties in a relationship of the form of (2), calibrated using the same 175 catchments and runoff events used to derive (1), with (b) the uncertainties in (1). However, this was beyond the scope of the current paper.

The argument above may be of interest in its own right but it also serves as a reminder that, in order to monitor progress during the course of the PUB Decade (2003-2012), it will be necessary to devise, agree upon, and apply methods and procedures by which reduction in predictive uncertainties can be demonstrated.

Sometimes in hydrology, low uncertainty in the quantity being estimated is associated solely with good precision (e.g. standard error), and consequently the accuracy (bias) component of uncertainty is overlooked. For example, it appears to have been assumed that (2) gives, on average, estimates of $Tp(0)$ for the gauged catchments used in its derivation (assuming them to be ungauged) no different from the 'observed' values of $Tp(0)$. However, equations of the form of (2) can introduce bias when they are the back-

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[1] http://iahs.info; http://cee.uiuc.edu/research/pub/

transformation of a regression model calibrated using logarithmically transformed variables [Ferguson, 1986]. Indeed, (1) and (2) were derived in this way. The bias arises as follows, using regression of *y* on *x* as an example.

The underlying model is given by (3), where *i* denotes the *i*th of the *n* values used for the regression analysis and ε_i is an independent additive error term from a normal distribution with a mean of zero and variance σ_ε^2, i.e. N(σ_ε^2, 0). After regression analysis to estimate $log(a)$ and α, (3) is back-transformed to (4), where $log(\eta_i) = \varepsilon_i$.

$$log\,(y_i) = log\,(a) + \alpha\, log\,(x_i) + \varepsilon_i \tag{3}$$

$$y_i = \eta_i \alpha\, x_i^a \tag{4}$$

$$E(\eta_i) = \exp\left(\sigma_\varepsilon^2\right) \tag{5}$$

The multiplicative errors, η_i, are therefore assumed to be log-normally distributed, in which case if natural logarithms were used, the expected value of η_i is given by (5) [Miller, 1984]. It can be seen from equation (5) that the bias is zero (i.e. $E(\eta_i)$ is unity) only if there is no scatter ($\sigma_\varepsilon = 0$) about the best-fit curve of $log(y)$ against $log(x)$, and that the bias increases as the scatter (σ_ε) increases.

In straightforward cases it is possible to quantify the bias and apply a correction factor. However, this does not appear to have been done for (1) or (2), or for some other cases of similar regionalisation equations in the literature [e.g. Abdulla and Lettenmaier, 1997; Sefton and Howarth, 1998]. The fine detail of the procedure by which (2) was derived means that it is difficult to establish the magnitude of its bias but Littlewood [2002b] considered it to be not less than 8%, with (2) systematically underestimating *Tp*(0). Therefore, not only does (2) give imprecise estimates for *Tp*(0) in ungauged catchments (+85%/-54%), it is inaccurate with a bias of perhaps more than 8%. Although a bias of 8% adds only about half of one percentage point to the combined root mean square error for (2), it is a component of the total error that modellers should consider and minimise whenever possible.

3. THE MIXED EXPONENTIAL DECAY UH

Employing the 6-parameter rainfall-runoff model that includes the 3-parameter mixed-exponential decay UH mentioned in the Introduction, Sefton and Howarth [1998] derived a regionalisation scheme for England and Wales. They calibrated the rainfall-runoff model for 60 gauged catchments over approximately 3-year records of daily data (taken from the period September 1986 to August 1989), using a parameter estimation and selection procedure described by Jakeman *et al*, [1990]: a trade-off between (a) a high proportion of initial variance in streamflow accounted for by the model and (b) a low 'average relative parameter error' on the UH parameters. The 60 catchments had flow regimes largely unaffected by anthropogenic effects. Sefton and Howarth [1998] subsequently derived six statistical relationships, one for each of the six model parameters, of the general form given by (2) but using different catchment characteristics. The correlation coefficients obtained ranged between 0.37 and 0.80 as shown in Table 1, where: *f* (^{o}C^{-1}) is a factor for temperature modulation of evaporative losses; τ_w [T^{-1}] controls the rate at which the catchment dries out in the absence of rainfall; 1/*C* [L] is the volume of a conceptual store expressed as a depth over the catchment; $\tau^{(q)}$ and $\tau^{(s)}$ [T] are decay time constants for the dominant quick and slow response UHs respectively; and $v^{(s)}$ [-] is the relative volumetric slow-flow throughput. The 894 km^2 Teifi at Glan Teifi was one of the 60 catchments used.

Table 1. Correlation coefficients for multiple regression regionalisation equations

DRC*	f	τ_w	C^{-1}	$\tau^{(q)}$	$\tau^{(s)}$	$v^{(s)}$
Coefficient of correlation	0.80	0.41	0.61	0.64	0.37	0.77

Source: Sefton and Howarth [1998]
* Dynamic response characteristic (independent variables)

Employing software [Littlewood *et al.*, 1997] now available free of charge[2], Littlewood [2002c] showed that, when the 6-parameter model and parameter identification procedure used by Sefton and Howarth [1998] were re-applied to the Teifi, there was a tendency for low flows to be over-estimated, i.e. $\tau^{(s)}$ was inaccurate (positively biased). However, when the parameter selection procedure was extended, by additionally adjusting parameter *f* by trial-and-error (holding τ_w constant and re-calibrating the other four parameters each time) in search of a better match between the low-flow end of flow duration curves for gauged and modelled flows, Littlewood [2002c] obtained a

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[2] See http://www.ceh.ac.uk/ or http://www.wmo.ch/web/homs/homshome.html - HOMS Component K22.2.11.

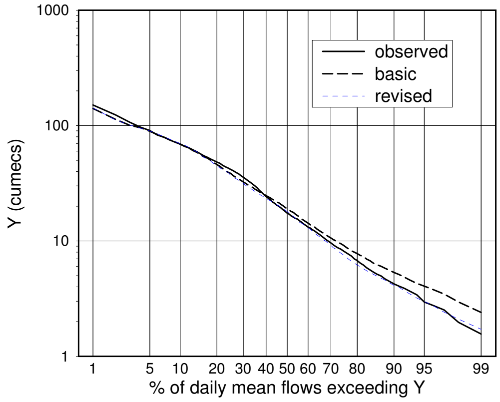

Figure 1 Teifi at Glan Teifi flow-duration curves 29th May 1980 to 25th June 1988 for observed and modelled flows by the basic and revised parameter selection procedures

better model for the Teifi. Figure 1 shows Teifi flow-duration curves associated with the basic and revised modelling methods: the revised method gives a good characterisation of the flow regime between the 1 percentile and 99 percentile. The revised parameter and selection procedure is a multi-objective, manual-automated hybrid, procedure similar to the approach discussed by Boyle *et al.* [2000] and Wagener *et al.* [2001].

An effect of the model improvement described above was to minimise bias in $\tau^{(s)}$, with $\tau^{(s)}$ decreasing from 48.8 days to 39.0 days (a 20% change). As suggested in Figure 1, the model-fit at high (quick response) flows changed only slightly, with $\tau^{(q)}$ decreasing from 1.99 days to 1.91 days (a 4% change). Littlewood [2003] compared the efficacy of the basic and revised parameter selection procedures for six other catchments in Wales, ranging in size from 129 km^2 to 1480 km^2. In four of the six cases the revised procedure clearly had a similar effect of minimising bias in $\tau^{(s)}$. Littlewood [2003] discussed likely reasons why the benefit of the revised procedure was not so apparent for the other two catchments, i.e. factors affecting the flow regime and the quality of flow measurements for the largest catchment and, for the other catchment (a highly responsive mountainous basin with a relatively high annual average rainfall of 2189 mm), the inadequacy of the daily modelling time-step used.

The bias in $\tau^{(s)}$ introduced by the basic parameter selection procedure used by Sefton and Howarth [1998] may partly explain the relatively poor correlation coefficient for $\tau^{(s)}$ (0.37) in Table 1. It is interesting to speculate, therefore, that the correlation coefficient of a regionalisation equation for $\tau^{(s)}$ using the revised procedure for the 60 catchments would be higher, perhaps similar to that for $\tau^{(q)}$ in Table 1 (0.64). Work to investigate this possibility is planned but it is worth remembering that, for flow regimes dominated by a quick flow response, e.g. the Teifi, the precision associated with $\tau^{(s)}$ is usually inferior to that for $\tau^{(q)}$, as will now be discussed further.

A feature of the modelling methodology introduced by Jakeman *et al.* [1990] is that indicative standard errors on $\tau^{(q)}$ and $\tau^{(s)}$ become available as a result of the UH parameter identification algorithm employed. For the Teifi, using the revised parameter selection procedure, 95% confidence limits for $\tau^{(q)}$ are +5.2%/-4.2%, and for $\tau^{(s)}$ they are +13.8%/-11.0%. For flow regimes dominated by a slow response the precision associated with $\tau^{(q)}$ is likely to be poorer than that for $\tau^{(s)}$ [Zlatunova *et al.*, 2002; Littlewood, 2002d]. Employing a relationship calibrated for gauged catchments dominated by a quick flow response, it may therefore be an unrealistic expectation to regionalise $\tau^{(s)}$ with respect to catchment characteristics as well as can be achieved for $\tau^{(q)}$, and *vice versa*. Clearly, however, the choice of which catchment characteristics (independent variables) to use in regression models for $\tau^{(q)}$ and $\tau^{(s)}$ (and for f, τ_w, C and $v^{(s)}$) is of paramount importance.

4. CONCLUDING REMARKS

The paper has highlighted the lack of precision in estimates of Tp for the triangular UH given by (1) and (2), and the relatively small bias (inaccuracy) in those estimates of Tp if left uncorrected. The 6-parameter rainfall-runoff modelling methodology referred to in this paper and described in greater detail elsewhere [e.g. Jakeman *et al.*, 1990; Littlewood, 2003] can often, if sufficient care is taken in the selection of its parameters, give a good characterisation of quick-response dominated natural flow regimes at a daily time-step. In addition to a close agreement between modelled and observed flows temporally, a good match between daily time-step flow-duration curves for modelled and observed daily flows over the 5-95 percentile range can be achieved in many cases, and sometimes, as for the Teifi, out to the 1 percentile and the 99 percentile (Figure 1). Contrary to a view that because of parameter identification difficulties different models are required for high and low flows [Wagener, 2003], the revised 6-parameter modelling methodology outlined here can, in many cases, model a wide range of the flow regime at daily time-step.

Visual inspection of flow duration curves plotted as in Figure 1 can be an extremely useful step in the assessment of rainfall-runoff models. Indeed, the author would suggest that it should be a required step. In the case presented here (Figure 1), and for other cases presented by Littlewood [2003], one of the loss module parameters (*f*) controls the position of the low-flow end of the flow duration curve to the extent that manual trial-and-error adjustment of that parameter leads to a revised set of model parameters that greatly improves the characterisation of the flow regime. Automation of this procedure as an additional step in the parameter identification and selection procedure would allow more efficient application of the approach to many catchments, as required for regionalisation.

It is evident from this paper and Littlewood [2003] that the full potential of the 3-parameter, mixed exponential decay, UH to assist with estimating flow regimes for ungauged catchments from rainfall, air temperature and catchment characteristics, has yet to be exploited. As a contribution to the PUB Decade, plans are being developed to further investigate this potential for catchments in the UK and other hydroclimatic zones.

Although the 6-parameter rainfall-runoff model and methodology referred to in this paper are often able to simulate continuous streamflow well, representation of processes by the model is simplistic (but superior to that of the triangular UH approach). This is both a strength and a weakness. It is a strength because the parametric parsimony of the model allows the parameters to be reasonably well identified from records of streamflow, rainfall and air temperature. It is reasonable to expect, therefore, that useful statistical relationships might be found between those parameters and catchment characteristics, leading to practical application for regionalisation to ungauged basins. Such a modelling methodology can be said to have good *utility*. However, the simplistic description of streamflow generation processes in the 6-parameter model is a weakness because it does not fully use, or advance, our *scientific understanding* of how catchments work.

Conceptually more complex models may not be the answer in a practical sense. A computer-based spatially distributed rainfall-runoff model that incorporates detailed process descriptions, which match our existing scientific understanding of how catchments work, can lack utility. They can require the calibration of so many parameters (many of which may be poorly estimated), and so much (costly) input data, that they are unsuitable for systematic application.

Hydrology is essentially a practical activity. The utility of a given modelling approach incorporated in a computer program is therefore of great value. However, hydrology is also a blend of sciences, where the ever-better understanding of underlying processes is a legitimate and important goal. It may not always be necessary to understand sub-catchment-scale processes in order to be able to contribute to solving real-world water resources and environmental management problems using appropriate computer models. But it may not be wise to live by that observation; it can result in the unsatisfactory and sometimes vulnerable situation whereby we achieve the right (good) answers for the wrong (only approximately correct) reasons. During the PUB Decade it should be possible to move towards a unification of utility and scientific understanding in computer models. Then we will be closer to achieving the right answers for the right reasons.

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