River Flow Simulation within Ungauged Catchments; the Utility of Regionalised Models

Andrew Young

N. S. Reynard

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A. R. Young, **N.S. Reynard**

Centre for Ecology and Hydrology (CEH) - Wallingford, Maclean Building, Crowmarsh Gifford. Wallingford, Oxfordshire, OX10 8BB.

Abstract: The extraction of information from hydrological data has been increased by the use of multiple objective functions which lead to trade off strategies during model calibration. Uncertainty within input data, model calibration and structure and parameter regionalisation schemes all led to uncertainty within model simulations when used as predictive tools. However, model success and failure is commonly determined not by abstract fit statistics but by the sensitivity of subsequent analyses to the uncertainty in the simulated stream flow data. This paper will explore some of these issues in the context of the assessment of potential impacts of climate change on river flows using the results from a UK case study on regionalising model parameters for a rainfall runoff model. The paper will comment on the utility of regionalised hydrological models for evaluating the impact of potential climate change scenarios using the specific example of a study from the United Kingdom and will conclude by outlining some current research directions in the regionalisation of rainfall runoff models and climate change impact assessment.

Keywords: Regionalisation, water resources, rainfall runoff modelling, climate change

1. INTRODUCTION

Access to daily stream flow data, at the river reach scale, is a central component of many aspects of water resource and water quality management. However, the majority of river reaches are ungauged hence there is an operational requirement for a quick, consistent and reliable method for simulating historical stream flow records within ungauged catchments. Furthermore, the coupling of hydrological models into land-surface schemes for Regional Climate Models (RCM) is central to improving the utility of these models in predicting the potential impacts of future climate change and variability on river flows.

Historically, the requirement for flow information within ungauged catchments has been met in the United Kingdom [NERC, 1980; Holmes et al., 2002a&b], and elsewhere [for an example see Demuth, 1994] through models that relate flow regime statistics to the physical and climatic properties of a catchment.

However, there are many applications for which a time series of stream flows is required. These include the assessment of yield for water resource schemes, the in-stream flow requirements of aquatic flora and fauna and the assessment of the impacts of climate change at the catchment scale. This has lead to renewed interest in the regionalisation of rainfall runoff models for estimating river flows within ungauged catchments for water resource and flood prediction purposes in the United Kingdom. The Centre for Ecology and Hydrology has maintained an active research programme in the regionalisation of rainfall at both an hourly time step for flood prediction purposes [Lamb, et al, 2000; Calver et al, 2001] and at a daily time step through the work of Arnell and Reynard [1996], Sefton and Boorman [1997] and Young [2002, 2004] for water resources. The outputs from the latter study are used in this paper. This study, in common with the other studies referenced, focused on the calibration of a simple rainfall runoff model within a wide range of catchment types and the subsequent development of multivariate relationships between catchment characteristics and calibrated model parameters. In this study the most effective relationships were derived using multivariate regression with the uncertainty in the estimation of a particular model parameter encapsulated as the standard error of the regression model.

The catchment model was based on the Probability Distributed Model (PDM) of Moore [1985]. The model assumes a Pareto (reflected power) distribution of storage capacity (defined by the maximum storage capacity, Cmax, and the shape parameter, b) and used a second order linear routing reservoir scheme for simulating quick and slow flow routing of effective rainfall (with time constants K1: quick flow and Kb: slow flow). There is also an interception storage term (parameter g) and a soil moisture related drainage term (controlled by parameter kg). The conceptual structure of the model is presented within Figure 1.

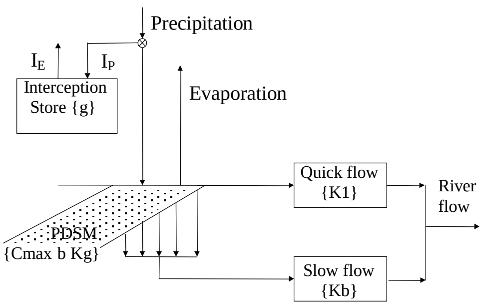


Figure 1. Conceptual structure of the model.

For the study, catchment average precipitation time series were derived for each catchment from the UK Meteorological Office daily rainfall library using the interpolation methodology of Jones [1983]. Time series of Potential Evaporation (PE) demand were estimated for each catchment using a scheme for disaggregating Meteorological Office of Rainfall and Evaporation Calculation System (MORECS) II [Hough, 1996] Penman Montieth PE estimates from a 40 to a 1 km resolution grid, taking into account the impact of increased spatial heterogeneity of topographic controls on PE.

The model was calibrated on the catchments using a multi-criterion, constrained random walk scheme that utilised a number of objective functions, allowed for trade-offs between different aspects of model fit and recognised that the input stream flow and climatic data have an associated uncertainty. This calibration scheme was used to yield up to 300 “valid” model parameter vectors identified for each catchment using a 6-10 year calibration period. All “valid” model parameters vectors were evaluated over an independent evaluation period (average 16 years) and the choice of one parameter vector for each catchment for subsequent use in the regionalisation study was based on performance over both the calibration period and the stability of fit over the evaluation period

2. EVALUATING THE POTENTIAL IMPACT OF CLIMATE CHANGE ON UK RIVER FLOWS

It is now recognised that human activities are leading to increases in greenhouse gas concentrations which may in turn lead to changes in climate [IPCC, 2001]. These changes in climate may result in changes in the hydrological cycle over Britain. Water providers and environmental regulators are increasingly incorporating an assessment of the impacts of climate change within water resources planning activities. Over the last few years there have been a number of studies which have looked at the potential effects of climate change on river flows in Britain [eg Arnell & Reynard, 1996; Arnell & Reynard, 2000; Pilling & Jones, 1999]. All of these studies have been based on applying changes in climate to observed catchment climate time series and simulating stream flow in the study catchments under current and perturbed climates; the so called delta change methodology. These studies have used a number of scenarios, most recently those published by the UK Climate Impacts Programme in 2002; the UKCIP02 scenarios [Hulme *et al*, 2002].

Ideally, the effects of climate change on stream flow would be determined by using a locally-calibrated and validated catchment model to simulate stream flow and running the current (also termed “baseline”) and perturbed time series through a water resources model. However, in practice catchment models exist for only a small proportion of the surface water supply sources in the United Kingdom. A “fast-track” approach to estimating the potential effects of climate change scenarios on streamflow and recharge was therefore developed to aid the water industry, and has recently been updated [Arnell, 2003] for the UKCIP02 scenarios.

The UKCIP02 scenarios comprise a set of four alternative future climates spanning a range of global emissions, namely the Low, Medium-Low, Medium-High and High Emissions scenarios, for three future 30-year time slices, the 2020s, 2050s and 2080s. For the 2020s the medium-high and medium-low are identical. The scenarios are presented as monthly changes, compared with the 1961-90 baseline, either percentage or absolute, in 15 climatic variables, for a 50 × 50 km grid across the UK.

In essence, the approach of Arnell [2003] presents two methods. Where a rainfall-runoff model is available the regionalised climate change factors should be applied to the input precipitation and potential evaporation data to determine the impacts of flows. Where no such model is available the regionalised runoff factors should be applied to naturalised monthly mean flows, to produce perturbed flow time series representing conditions under a changed climate in the 2020s. These change factors are regionally extrapolated from catchment applications of the delta change methodology using locally calibrated rainfall runoff models. Within ungauged catchments and catchments with anthropogenically modified flow regimes there remains the problem that the pre-requisite naturalised flow time series has to be generated.

This paper builds on the work of Arnell to explore whether a regionalised model can be used to generate both the baseline naturalised flow time series within a catchment and subsequently apply the delta change methodology directly without the need to use the extrapolated regional factors. Through case study examples the paper explores whether the climate change signal in stream flow changes can be differentiated from the uncertainty associated with the identification of rainfall runoff model parameters, using predictions for the 2020s. This is tested for the case of a locally calibrated rainfall runoff model, where the model parameters are estimated from stream flow data and the case where the model parameters are estimated directly from catchment characteristics.

3. CASE STUDY CATCHMENTS AND APPLICATION OF THE DELTA CHANGE METHODOLOGY

The delta change methodology, using 2020s climate change factors for precipitation and PE, was applied to five medium sized catchments representing a broad cross section of climatic regimes within the United Kingdom using the model calibrations and regionalised parameter predictions from Young's regionalisation study. The locations of these catchment are presented within Figure 2.

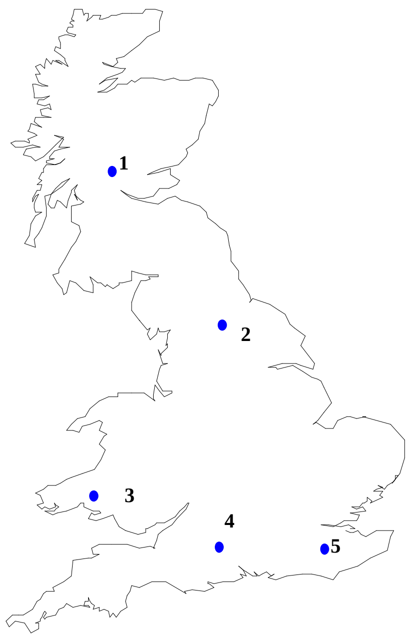


Figure 2. Catchment locations

These catchments were selected as the recorded flows are essentially natural and the calibrated model fits within these catchments were stable when the calibrated model was applied to an independent evaluation period of record. The calibrated and regionalised model parameters for these catchments are presented in Table 1. The results from the application of the delta change methodology for both the calibrated and regionalised models for these catchments are summarised for the medium-high emissions scenario case in Tables 2 and 3 respectively. The results are presented as percentage changes in the flow that is equalled or exceeded for 95% of the time, the mean flow and the mean flows within each calendar month.

These all show a significant decline in summer flows. The differences in predicted percentage change between the simulations obtained using regionalised parameter estimates and those obtained using the calibrated model parameters are less than 5% with the exception of the summer flow statistics highlighted for catchment 5 and Q95 for catchment 1. Catchment 1 is a very low baseflow catchment, the absolute value of Q95 is low and hence 5% corresponds to a small volumetric difference

Table 1. Calibrated and regionalised model parameter values for the case study catchments.

Catchment	Model Parameters					
	g	Cmax	b	kg	K1	kb
Calibrated						
1	1.9	105	0.8	857	49	408
2	1.7	102	2.7	746	64	542
3	2.1	217	3.8	719	42	683
4	1.5	141	0.1	1695	117	1599
5	1.6	145	0.1	5968	56	1673
Regionalised						
1	1.9	94	2.8	745	47	674
2	1.7	97	2.0	580	53	737
3	2.1	162	1.4	627	66	856
4	1.5	360	0.4	3269	154	1422
5	1.6	123	0.4	2731	54	761

Table 2. Percentage changes in selected flow statistics for the case study catchments using calibrated model parameters

		1	2	3	4	5
	Q95	-17	-16	-18	-16	***-18***
	MF	-2	-3	-4	-6	-9
Mean monthly flows	J	3	5	5	-1	4
	F	1	4	3	2	3
	M	0	1	1	-1	0
	A	-2	-3	-3	-2	-6
	M	-8	-11	-12	-4	-10
	J	-15	-19	-19	-8	-17
	J	-21	-24	-24	-12	***-18***
	A	-18	-23	-26	-16	***-25***
	S	-11	-17	-18	-20	***-38***
	O	-3	-6	-8	-21	***-32***
	N	3	1	0	-16	***-19***
	D	4	4	5	-6	-4

Catchment 5, the River Medway measured at Chafford Weir, lies in the drier, south east of England. Within this catchment, the correct simulation of the soil moisture internal state variable within the model and the subsequent modelling of evaporation losses and the reduction of summer evaporation to below potential evaporation rate will be critical. The model behaviour within this catchment was investigated further using an ensemble simulation approach to evaluate whether the climate change signal in precipitation and evaporation predicted by the medium-high emission scenario climate perturbations was significant in the context of simulation uncertainty resulting from model parameter uncertainty for both the calibrated and regionalised case.

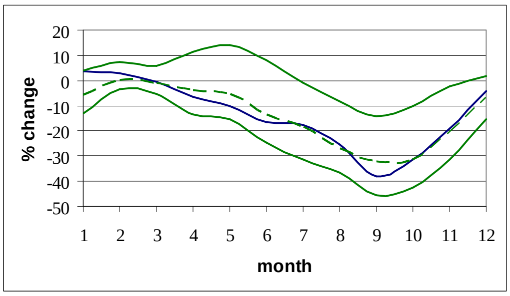
Table 3. Percentage changes in selected flow statistics for the case study catchments using regionalised model parameters [Young, 2004]

		1	2	3	4	5
	Q95	-12	-15	-17	-19	***-24***
	MF	-2	-3	-4	-7	-6
Mean monthly flows	J	3	5	4	-3	5
	F	1	4	3	-1	4
	M	0	2	1	-1	1
	A	-2	-2	-2	-2	-4
	M	-8	-9	-8	-5	-11
	J	-15	-17	-15	-10	***-21***
	J	-18	-22	-21	-13	***-28***
	A	-16	-23	-26	-19	***-34***
	S	-9	-17	-20	-22	***-33***
	O	-2	-7	-10	-20	***-20***
	N	3	0	-2	-14	***-9***
	D	4	4	4	-7	1

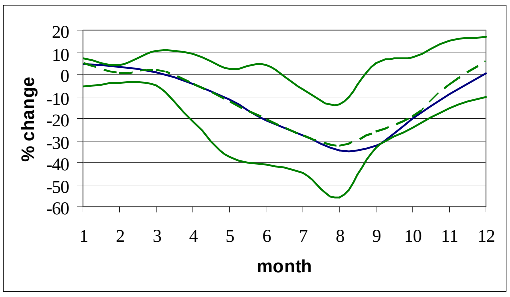
4. UNCERTAINTY ANALYSIS FOR THE MEDWAY AT CHAFFORD WEIR.

Within this catchment the sensitivity of calibrated model results to the selection of model parameters was evaluated by repeating the application of the delta change methodology using the 300 candidate “equally valid” calibrated model parameter vectors identified for this catchment as part of the regionalisation study.

The sensitivity of the delta change methodology results obtained for the regionalised model was investigated through an ensemble set of 3000 applications of the methodology. These used random realisations of regionalised parameters based on mean predicted values from the multivariate regression models, the standard errors for the regression models assuming a Gaussian distribution for the error model. For the catchments considered the average standard errors for the prediction of model parameters, expressed as a fraction of the predicted values, were; Cmax: 0.58, b: 0.26, Kg: 0.70, K1: 0.57 and Kb: 0.40.



a) Calibrated model parameters



b) Regionalised model parameters

Figure 3. Non-parametric 68% confidence limits for predictions of changes in mean monthly flows

The results from these ensemble simulations are presented in Figure 3 for both the calibrated and regionalised model parameters. These figures present the change in monthly mean flows from the base line simulated mean flows as non-parametrically derived 68% confidence intervals (lighter traces). The median simulation are presented as dashed lines for both experiments and the results for the selected calibrated model parameters and the mean predicted regionalised model parameters are presented as darker traces.

These results clearly demonstrate that the propagation of the climate change signal, resulting in a decline in summer flows, is significant at this level of confidence for both the calibrated and regionalised model cases.

The asymmetric nature of the confidence interval for the regionalised case is probably a consequence of failing to incorporate correctly the residual parameter covariance within the model that is implicitly captured within the set of 300 calibrated model parameter vectors.

5. CONCLUDING REMARKS

This paper illustrates that the climate change signal from a particular scenario is significantly strong, in terms of its impact on the flow statistics used, to be robust in the light of both calibrated and regionalised parameter estimation uncertainty. This is encouraging in light of the practical application of regionalised models within this context and the coupling of such models to RCMs.

For future research it is anticipated that there will be a greater focus on the representation of evaporation processes within this class of model; this will give greater confidence to the predictions of potential impacts within climatic regimes in which evaporation limiting soil moisture deficits are common in most years. Furthermore, reductions in parameter uncertainty will be sought through the integration of catchment characteristics in the process of defining both model structure and regional parameter sets.

Turning to the climate change scenarios, there are many sources of uncertainty in any set of climate simulations. The current study uses just one emissions scenario, fed through one set of climate models (global and regional). There is considerable uncertainty surrounding the socio-economic assumptions that will drive future emissions, as there is in the modelling of the global and regional climate responses to these changes. This is particularly true for local and extreme precipitation, when different global models can predict either increases or decreases.

The level of climate impact is also strongly dependent on the method used to translate monthly percentage changes in rainfall to the corresponding changes at a daily timescale (arguably, a better alternative to the simple delta change method), and to translate relatively coarse, grid-scale changes into catchment-specific scenarios. These sources of uncertainty should be considered along with the hydrological uncertainty.

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