CORE
Metadata, citation and similar papers at core.ac.uk
Provided by NERC Open Research Archive

Predictions in Ungauged Basins: PUB Kick-off (Proceedings of the PUB Kick-off meeting held in Brasilia, 20–22 November 2002). IAHS Publ. 309, 2007.

Unit hydrograph characterization of flow regimes leading to streamflow estimation in ungauged catchments (regionalization)

I. G. LITTLEWOOD[1], A. J. JAKEMAN[2], B. F. W. CROKE[2], T. S. KOKKONEN[3] & D. A. POST[4]

1 *Centre for Ecology and Hydrology, Wallingford, Oxon OX10 8BB, UK*
igl@ceh.ac.uk
2 *Centre for Resource and Environmental Studies, The Australian National University, Building 43, Biology Place, Canberra, Australian Central Territory 0200, Australia*
3 *Laboratory of Water Resources, Helsinki University of Technology, PO Box 5200, FIN-02015 HUT, Finland*
4 *CSIRO Land and Water, GPO Box 1666, Canberra 2601, Australia*

Abstract The IHACRES rainfall–streamflow modelling approach provides a powerful set of techniques for assisting with parametrically efficient regionalization of streamflow response characteristics (unit hydrograph and loss module parameters) from inputs of rainfall, evaporation surrogates and physical catchment descriptor data. Recent work has indicated where further improvements can be made to the model structure and its model parameter estimation procedure, for regionalization work. IHACRES could, therefore, form a useful component of PUB, whence its continuing development would benefit greatly from application to PUB data sets and exposure to the wider PUB community. In order to register IHACRES at the Brasilia PUB kick-off meeting, and to seek comments as to how it might best contribute to the PUB Decade, this paper has the following objectives: (1) to outline the IHACRES approach and techniques, and their roles in assisting with regionalization; (2) to discuss the relevance of IHACRES within PUB; and (3) to propose an IHACRES component of PUB.

Key words Prediction in Ungauged Basins (PUB); rainfall–streamflow modelling; regionalization; unit hydrographs

IHACRES AND REGIONALIZATION

IHACRES is the acronym for the modelling system "Identification of unit Hydrographs and Components from Rainfall, Evaporation and Streamflow data" (Jakeman *et al.*, 1990). It is an approach which attempts to capture identifiable catchment-scale dynamic response characteristics (DRCs) from such data. Because the DRCs can be used to discriminate between the behaviour of catchments, an important application of IHACRES is assisting with regionalization (information transfer from gauged to ungauged basins) (Jakeman *et al.*, 1992; Littlewood & Jakeman, 1994). As shown at the core of Fig. 1 the IHACRES model structure, which often allows continuous hydrograph separation into dominant quick and slow components of streamflow, comprises two modules in series: a nonlinear loss module (parameters C, τ_w and f) linking rainfall and air temperature at time-step k (r_k and t_k) to effective rainfall (u_k); and a linear unit hydrograph (UH) module (parameters $\tau^{(q)}$, $\tau^{(s)}$ and $v^{(s)}$) linking u_k to streamflow (x_k). The six parameters, or dynamic response characteristics

Copyright © 2007 IAHS Press

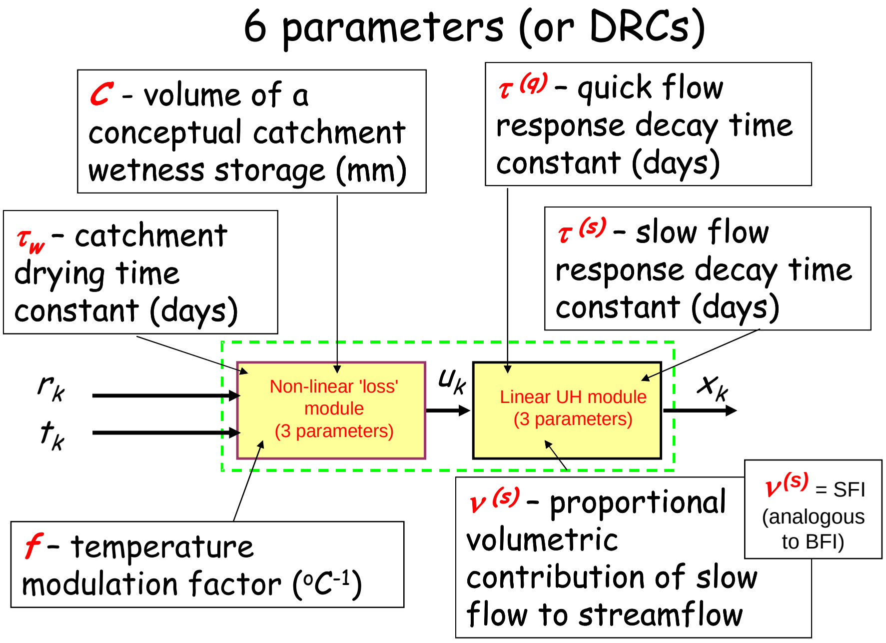

Fig. 1 Six parameters, or dynamic response characteristics (DRCs).

(DRCs) described in Fig. 1 can reasonably be expected to be associated with basin-scale physical catchment descriptors (PCDs) such as slope, stream density, land-use, etc. The loss module referred to in Fig. 1 is of the “catchment wetness index/low pass filter” type. Enhancements to, and variants of, this loss module have been applied for arid-zone or snow-affected catchments (Ye *et al*., 1997; Schreider *et al*., 1996, 1997; Steel *et al*., 1999). Alternative types of loss module, in line with widely accepted concepts of soil moisture deficit and water movement through vegetation canopies and idealized soil columns, have also been developed and applied with the same UH module (Evans & Jakeman, 1998; Littlewood, 2002a; Croke & Jakeman, 2004).

IHACRES has been applied to a wide range of catchment types and for regionalization studies in the UK (Sefton & Howarth, 1998), Australia (Post & Jakeman, 1996, 1999) and North America (Post *et al*., 1998; Kokkonen *et al*., 2003). Recent work has: (a) led to improvements in the IHACRES model selection procedure for regionalization of the flow regime (5–95 percentile flows) for rivers in Wales (Littlewood, 2002b,c, 2003); and (b) exposed a pitfall for the unwary whereby bias can be introduced in regionalization equations derived from multiple regression of rainfall–runoff model parameters (e.g. DRCs from IHACRES) on PCDs (Littlewood, 2002d). In practice, calibration and selection of a “best” IHACRES model from many apparently good models for a given catchment involves avoiding those that perform well in calibration-mode but poorly in simulation-mode (Littlewood, 2001).

Other recent developments of IHACRES include UH identification using only streamflow data (Croke, 2006) (for situations where rainfall data are sparse or unavailable) and the use of groundwater level and/or evapotranspiration data as additional exogenous variables for model calibration (Croke *et al*., 2002). Another important aspect of improving methods to regionalize hydrological response is understanding the influence of land-use variations on streamflow regimes (Croke &

Jakeman, 2001). Most progress has been made with small experimental catchments subject to comprehensive land-use changes (Post *et al.*, 1998; Kokkonen & Jakeman, 2002; Dye & Croke, 2003). The effect of mosaic patterns of land-use on hydrology remains a problem. Two promising methods that have been used in conjunction with IHACRES for addressing this issue are: the integration of plot-scale vegetation models with catchment-scale hydrological models (Merritt *et al.*, 2002); and the use of catchment-scale empirical relationships (Zhang *et al.*, 2001) to determine evapotranspiration for different vegetation types (Croke, 2002).

As an example of an IHACRES application, Figs 2 and 3 show time series and flow duration curves (FDCs), respectively, for observed and modelled daily streamflow for the 894 km^2 catchment of the River Teifi to Glan Teifi in Wales (Littlewood, 2002c). The model accounts for 88% of the variance of streamflow over its calibration period and has the following DRCs: τ_w = 22 days, f = 2.0°C^{-1}, C = 69 mm, $\tau^{(q)}$ = 1.91 days, $\tau^{(s)}$ = 39.0 days and $v^{(s)}$ = 0.36 (dimensionless). The FDCs in Fig. 3 confirm that the model performs well over the 5–95 percentile flow range. The hydrological regime at Glan Teifi is characterized, therefore, by the six DRCs described in Fig. 1. Given similar models for other gauged catchments, statistical relationships can be sought that link DRCs and PCDs; these DRC–PCD relationships can then be applied to ungauged catchments.

An alternative to the regionalization of the parameters of a model is to regionalize aggregate measures of the hydrological response such as water yield and flow probability distribution, and use these to constrain the model parameters. Using the water yield from similar neighbouring catchments has resulted in improved prediction of flows using a regionalization approach (Post *et al.*, 1998). This can be extended through regionalization of the runoff coefficient, enabling prediction across a larger scale (Croke, 2002). If the model parameters are calibrated using the flow duration curve (FDC) rather than the time series of flow, the concept can be further extended to calibration of the model to the regionalized probability distribution, avoiding the need to determine the relationships between model parameters and PCDs. Such an approach

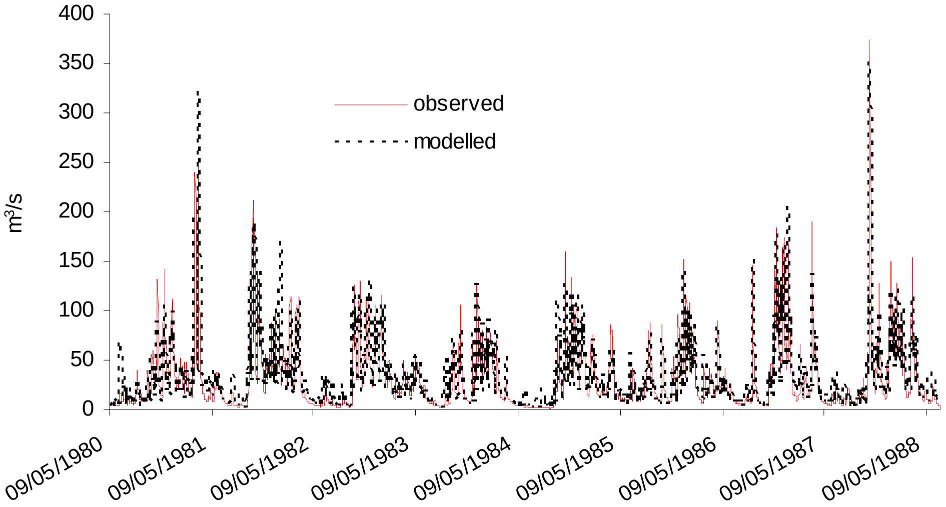

Fig. 2 Teifi at Glan Teifi calibration model-fit 9 May 1980 to 25 June 1988.

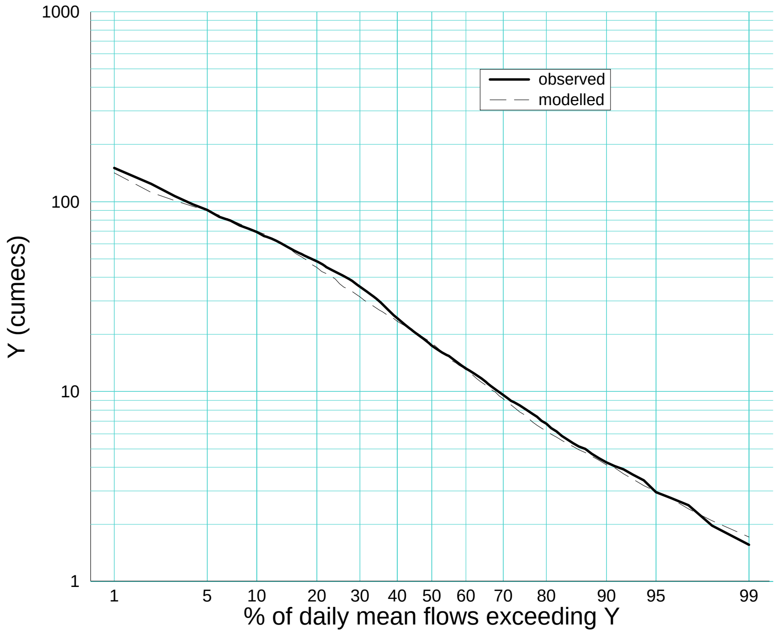

Fig. 3 Teifi at Glan Teifi flow duration curves 9 May 1980 to 25 June 1988.

has not been tried previously, but preliminary work has been carried out on catchments in the Murray-Darling Basin in Australia (Croke, 2002). Other recent work (Littlewood, 2003) has demonstrated how, for several catchments in Wales, IHACRES model-fits can be substantially improved at low flows by using FDCs as an *additional* step to a “standard” model calibration procedure.

IHACRES AND PUB

From material posted on the PUB web site (September 2002) it is clear that the need for the programme to adopt a range of techniques and approaches has been recognized at the outset of the PUB Decade. The PUB programme will look at wide ranges of catchment types, climatic zones, hydrological variables and levels of data availability. A regionalization technique suitable for one part of the world may not be applicable or appropriate in another. However, it is envisaged that much can be learned from regionalization in parts of the world where hydrometric networks and data management systems are relatively good. Knowledge thus gained will be of use in regions where data are not so good or so readily available. Prediction in ungauged basins within regions where relevant data from ground measurements are of good quality, and are readily available, will be of higher quality than in regions where data are not of such good quality, or may not exist (where even more indirect methods will be required). PUB will need to be concerned with the uncertainties associated with the different regionalization techniques it investigates and develops. The uncertainties associated with the different methods will provide indices of the value of data from measurement networks (e.g. whether on the ground or from satellites). The premise that “Hydrological data are an endangered species” rings true, especially in some regions. PUB should concern itself with establishing the value of measurements to water resources planning, environmental management, etc., and with presenting this information to decision-makers in order to help halt this trend towards fewer data. The value of hydrological data will be apparent from the relatively large uncertainty associated with estimates in ungauged basins based on the more indirect methods. The modelling and regionalization approach outlined in this paper can assist in this venture by providing a benchmark (indicative upper limit) guide to the quality of regionalization schemes based on ground-observed hydrological data.

According to PUB definitions (IAHS, 2002a) an ungauged basin with respect to streamflow cannot be a gauged basin with respect to either sediment or water quality. PUB therefore implicitly recognizes that streamflow is a key variable for water, sediment and hydrochemical budget calculations. Estimation of continuous streamflow is a main focal point of IHACRES. The authors agree that in order for PUB to pursue the estimation of streamflow in ungauged basins it must review techniques currently available for modelling streamflow in gauged basins (and for the subsequent transfer to ungauged basins of the information gained thereby) and develop them further. In terms of accuracy and precision in the estimated flows they provide for ungauged basins, regionalization schemes based on information obtained from existing conventional hydrometric networks are likely to be located at the better end of the spectrum of techniques that PUB will investigate. Furthermore, unless a given technique for information transfer to ungauged basins can be demonstrated to work adequately for gauged basins (assuming a given gauged catchment to be ungauged for that purpose) it can claim to have little or no scientific basis; in the absence of validation in this way the efficacy of the technique cannot be judged objectively. It is evident, therefore, that although PUB is primarily concerned with estimating hydrological variables in ungauged catchments, it will need to develop and test techniques on gauged basins. The quality of the gauged-catchment data employed for this purpose will, of course, be important.

For gauged catchments, IHACRES can often identify separate unit hydrographs for dominant quick and slow flow responses (subject to good-quality data, essentially natural flow regimes and non-exotic catchment-scale hydrological behaviour). Streamflow (and a continuous hydrograph separation) is synthesized by convoluting the quick and slow unit hydrographs with effective rainfall. A guiding principle for IHACRES modelling of catchments in developed countries (where there are more-or-less good hydrometric networks) has been the pursuit of an adequate simulation of continuous streamflow using (more-or-less) readily available data (e.g. daily rainfall, streamflow and an evaporation surrogate such as air temperature), via a parametrically parsimonious model. A motivation for the parsimonious approach is the widely accepted recognition that it is not possible to identify, with useful precision, more than about six parameters from such data sets (Jakeman & Hornberger, 1993). Importantly in the context of PUB, a model with a few well-identified parameters (DRCs), rather than many less-well-identified parameters, has the advantage that better statistical relationships can be expected between those few parameters (DRCs) and the selected PCDs, leading to regionalization (estimation of streamflow in ungauged catchments from inputs of rainfall, air temperature, and DRCs estimated from PCDs).

The initial development of IHACRES (Jakeman *et al.*, 1990) marked an advance in the application of unit hydrograph theory. Previously, unit hydrographs were commonly used only for quantitative aspects of "high flow" hydrology, where the baseflow during runoff events was estimated separately by some other method. The simultaneous identification of unit hydrographs for both high and low flows by IHACRES (e.g. the Teifi model-fit illustrated in Figs 1 and 2) extends the utility of the UH approach to include a large portion of the whole flow regime (Littlewood, 1998). Notwithstanding that some tracer field studies suggest that the conceptual representation of catchment-scale streamflow generation processes in IHACRES is imperfect (the model structure is, of course, a gross simplification of reality), the continuous hydrograph separation facilitated by the methodology provides a time-variant mixing ratio and an overall Slow Flow Index, SFI, analogous to the well-known Base Flow Index, BFI, that have potential utility for regionalization of water quality. Within PUB it would be of great interest to pursue water quality regionalization issues related to IHACRES streamflow modelling. However, regionalization of water quantity (streamflow regimes) should remain a priority because it is a key variable in water resources evaluation, sediment and water quality budgets, and ecohydrology studies.

From the foregoing it is evident that IHACRES is relevant to themes 1, 2 and 3 of the PUB Scientific Programme (IAHS, 2002b): Theoretical Hydrology; Observational Hydrology; and Model Diagnostics and Inter-Comparison. It may also be of utility in theme 4 (Advanced Data Collection Techniques), e.g. modelling streamflow dynamics using a catchment wetness index derived from Earth Observation methods. There was recognition at the PUB Preparatory Workshop (Kofu, March 2002), of the potential utility to PUB of the IHACRES modelling approach. Generically, IHACRES is of the "data based mechanistic" type (Young, 2002) referred to in the PUB Programme (IAHS, 2002c) and, as such, is able to make efficient use of existing data sets. For example, DRC–PCD relationships have been established based on IHACRES models for 60 UK catchments (Sefton & Howarth, 1998). The daily streamflow data were readily available from the UK National River Flow Archive (NRFA). A result of that study was moderately successful estimation of the daily hydrograph at ungauged sites, from inputs of rainfall, air temperature and DRCs estimated from PCDs. However, recent work (Littlewood, 2003) has indicated that it would be possible to make substantial improvements to this regionalization scheme, particularly with respect to low flows. PUB provides an umbrella initiative under which such improvements can be encouraged, with a view towards extending the work geographically to accommodate: (a) other regions with similar availability of data; and (b) regions with less available data.

Ongoing work (e.g. Littlewood, 2007) has: (a) demonstrated for one of the Plynlimon research catchments, Wales, a strong dependency of IHACRES DRCs on the data time-step employed for model calibration; and (b) discussed the implications of this in the context of regionalization using IHACRES and other rainfall–streamflow models. PUB will allow this issue to be investigated internationally using a wide range of catchments and different modelling approaches.

CONCLUDING REMARKS AND PROPOSAL

The authors believe that IHACRES has much to offer PUB. Work along the lines given in this paper would benefit greatly from interaction with other PUB participants.

Indeed, the authors regard interaction between groups as essential and would therefore welcome reciprocal keen interest and close involvement from other PUB participants in the work outlined here. It is proposed that: (a) the authors form a core PUB group to apply and further develop the IHACRES methodology (meaning its several structural variants and recent developments related to better characterization of the whole flow regime) to assist with the wider objectives of PUB; and (b) this group interacts with any other PUB group where it would be mutually beneficial.

POSTSCRIPT

This paper is based on a presentation at the PUB Kick-off meeting held in Brasilia in 2002, with more recent material added as appropriate. For the most part, IHACRES modelling for PUB is associated with the Top-Down modelling Working Group (TDWG). Information about the TDWG (how to make contributions, meetings, publications, etc.) can be obtained via the PUB and TDWG websites at http://pub.iwmi.org and http://www.stars.net.au/tdwg/, respectively.

REFERENCES

Croke, B. F. W. (2002) Improving the Hydrological Parameterisation of SedNet. Technical Report I, Basin-wide mapping of sediment and nutrient exports in dryland regions of the Murray-Darling Basin, September 2002.

Croke, B. F. W. (2006) A technique for deriving an average unit hydrograph from streamflow-only data for ephemeral quick-flow-dominant catchments. *Adv. Water Resour.* **29**, 493–502.

Croke, B. F. W., Smith, A. B. & Jakeman, A. J. (2002) A one-parameter groundwater discharge model linked to the IHACRES rainfall–runoff model. In: *Proc. 1st Biennial Meeting of the International Environmental Modelling and Software Society* (ed. by A. Rizzoli & A. Jakeman), Vol I, 428–433. University of Lugano, Switzerland.

Croke, B. F. W. & Jakeman A. J. (2001) Predictions in catchment hydrology: an Australian perspective. *Mar. Freshwater Res*. **52**, 65–79.

Croke, B. F. W & Jakeman, A. J. (2004) A catchment moisture deficit module for the IHACRES rainfall–runoff model**.** *Environ. Modelling & Software* **19**, 1–5.

Dye, P. J. & Croke B. F. W. (2003) Evaluation of streamflow predictions by the IHACRES rainfall–runoff model in two South African catchments. *Environ. Modelling & Software* **18**, 705–712.

Evans, J. P. & Jakeman, A. J. (1998) Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. *Environ. Modelling & Software* **13**, 385–393.

IAHS (2002a) PUB Programme, draft 11 June 2002, section 1.1, p. 5.

IAHS (2002b) PUB Programme, draft 11 June 2002, p. 3.

IAHS (2002c) PUB Programme, draft 11 June 2002, section 1.5.2, p. 8.

Jakeman, A. J. & Hornberger, G. M. (1993) How much complexity is warranted in a rainfall–runoff model? *Water Resour. Res*. **29**(8), 2637–2649.

Jakeman, A. J., Littlewood, I. G. & Whitehead, P. G. (1990) Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. *J. Hydrol*. **117**, 275–300.

Jakeman, A. J., Hornberger, G. M., Littlewood, I. G., Whitehead, P. G., Harvey, J. W. & Bencala, K. E. (1992) A systematic approach to modelling the dynamic linkage of climate, physical catchment descriptors and hydrologic response components. *Mathematics Computers Simulation* **33**, 359–366.

Kokkonen, T. S. & Jakeman, A. J. (2002) Structural effects of landscape and land use on streamflow response. In: *Environmental Foresight and Models: A Manifesto* (ed. by M. B. Beck), 303–321. Elsevier Science BV, The Netherlands.

Kokkonen, T. S., Jakeman, A. J., Young, P. C. & Koivusalo, H. J. (2003) Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. *Hydrol. Processes* **17**, 2219–2238.

Littlewood, I. G. (1998) Continuous flow simulation using unit hydrographs characteristic of total streamflow. *Circulation, Newsletter British Hydrol. Soc.* **58**, 9.

Littlewood, I. G. (2001) Practical aspects of calibrating and selecting unit hydrograph-based models for continuous flow simulation. *Hydrol. Sci. J.* **46**(5), 795–811.

Littlewood, I. G. (2002a) Sequential conceptual simplification of the effective rainfall component of a rainfall-streamflow model for a small Kenyan catchment. In: *Proc first Biennial Meeting Int. Environmental Modelling and Software Society* Vol I (ed. by A. Rizzoli & A. Jakeman), 422–427. University of Lugano, Switzerland.

Littlewood, I. G. (2002b) An improved procedure for identifying quick and slow response unit hydrographs for regionalization of high and low flows. In: *Proc. Eighth National BHS Hydrology Symposium* (University of Birmingham, 8–11 September, British Hydrological Society), 121–126.

Littlewood, I. G. (2002c) Improved unit hydrograph characterisation of the daily flow regime (including low flows) of the River Teifi, Wales: towards better rainfall-streamflow models for regionalization. *Hydrol. Earth Systems Sci*. **6**(5), 899–911.

Littlewood, I. G. (2002d) A source of bias in regionalization equations. *Circulation, Newsletter of the British Hydrological Society* **72**, 9–11.

Littlewood, I. G. (2003) Improved unit hydrograph identification for seven Welsh rivers: implications for estimating continuous streamflow at ungauged sites. *Hydrol. Sci. J.* **48**(5), 743–762.

Littlewood, I. G. (2007) Rainfall–streamflow models for ungauged basins: uncertainty due to modelling time-step. In: *Euromediterranean Network of Experimental and Representative Basins (ERB2006)* (Proc. Eleventh Biennial Conf. 13–17 October 2006, Luxembourg). UNESCO Technical Documents in Hydrology Series.

Littlewood, I. G. & Jakeman, A. J. (1994) A new method of rainfall–runoff modelling and its applications in catchment hydrology. In: *Environmental Modelling*, Vol. II (ed. by P. Zannetti), 143–171. Computational Mechanics Publications, Southampton, UK.

Merritt, W. S., Croke, B. F. W. & Jakeman, A. J. (2002) Sensitivity testing of a biophysical toolbox for exploring water resources utilisation and management options. In: *Proc first Biennial Meeting Int. Environmental Modelling and Software Society* Vol I (ed. by A. Rizzoli & A. Jakeman), 311–316. University of Lugano, Switzerland.

Post, D. A. & Jakeman, A. J. (1996) Relationships between physical descriptors and hydrologic response characteristics in small Australian mountain ash catchments. *Hydrol. Processes* **10**, 877–892.

Post, D. A. & Jakeman, A. J. (1999) Predicting the daily streamflow of ungauged catchments in SE Australia by regionalising the parameters of a lumped conceptual rainfall–runoff model. *Ecol. Modelling* **123**, 91–104.

Post, D. A., Jones, J. A. & Grant, G. E. (1998) An improved methodology for predicting the daily hydrologic response of ungauged catchments. *Environ. Modelling & Software* **13**, 395–403.

Schreider, S., Yu, W., Jakeman, A. J., Whetton, P. H. & Pittock, A. B. (1996) Estimation of climate impact on water availability and extreme events for snow-free and snow-affected catchments in the Murray-Darling basin. *Australian J. Water Resour.* **2**, 1–13.

Schreider, S., Yu, W., Whetton, P. H., Jakeman, A. J. & Pittock, A. B. (1997) Runoff modelling for snow-affected catchments in the Australian alpine region, eastern Victoria. *J. Hydrol*. **200**, 1–23.

Sefton, C. E. M. & Howarth, S. M. (1998) Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. *J. Hydrol*. **211**, 1–16.

Steel, M. E., Black, A. R., Werritty, A. & Littlewood, I. G. (1999) Re-assessment of flood risk for Scottish rivers using synthetic runoff data. In: *Hydrological Extremes: Understanding, Predicting, Mitigating* (ed. by L. Gottschalk, J-. C. Olivry, D. Reed & D. Rosbjerg), 209–215. IAHS Publ. 255. IAHS Press, Wallingford, UK

Ye, W., Bates, B. C., Viney, N. R., Sivapalan, M. & Jakeman, A. J. (1997) Performance of conceptual rainfall–runoff models in low-yielding ephemeral catchments. *Water Resour. Res*. **33**(1), 153–166.

Young, P. C. (2002) Data-based mechanistic and top-down modelling. In: *Proc first Biennial Meeting Int. Environmental Modelling and Software Society* Vol I (ed. by A. Rizzoli & A. Jakeman), 363–374. University of Lugano, Switzerland.

Zhang, L., Dawes, W. R. & Walker, G. R. (2001) The response of mean annual evapotranspiration to vegetation changes at the catchment scale. *Water Resour. Res*. **37**, 701–708.