Engineers Australia
29th Hydrology and Water Resources Symposium
21–23 February 2005, Canberra

Redesign of the IHACRES rainfall-runoff model

B.F.W. Croke[1,2], F. Andrews[1], A.J. Jakeman[1,2], S. Cuddy[1,3], A. Luddy[1]
[1] Integrated Catchment Assessment and Management Centre, School for Resources, Environment and Society, The Australian National University, Canberra, ACT 0200 Australia
Email: Barry.Croke@anu.edu.au

[2] Centre for Resource and Environmental Studies, The Australian National University, Canberra, ACT 0200 Australia

[3] CSIRO Land and Water, Canberra

ABSTRACT: The PC-WINDOWS version of the IHACRES rainfall-runoff model (Littlewood et al, 1997) has been extensively used in surface water hydrology applications. The core of the model consists of a non-linear loss module that converts rainfall into effective rainfall, and a linear routing module that converts effective rainfall into streamflow. Recent construction of a new class of non-linear loss modules, as well as alternative model calibration techniques, has resulted in a redevelopment of the model. The redevelopment has been carried out in the Java programming language in order to make the model more widely available. The model is available through the Catchment Modelling Toolkit (http://www.toolkit.net.au). New features included in the new version of the model include: the original non-linear loss module (including the extension for ephemeral catchments made by Ye et al, 1997); extension of the linear routing module to include all possible second order transfer functions; a cross correlation tool; additional goodness of fit indicators; visualisation tools including zoomable and 3-D plots. Features currently underdevelopment include baseflow filtering, direct estimation of the unit hydrograph, spectral analysis tools and the catchment moisture deficit version of the non-linear module.

INTRODUCTION

Successful management of water resources requires qualitative analysis of the effects of changes in climate and land use practices on streamflow and water quality. While expert knowledge can provide indications of such impacts, detailed analysis requires the use of mathematical models to separate the water balance dynamically (at the temporal scale at which the important processes are operating). This includes separation of incident precipitation into losses to evapotranspiration, runoff to streams, recharge to groundwater systems and changes in short-term catchment storages. Some of the processes which need to be considered are: evapotranspiration and feedback to the atmosphere; vegetation dynamics; groundwater levels and the resulting effect on soil waterlogging and salinisation; reservoir storage capacity reliability; wetland dynamics; urban runoff; flooding; erosion in crop and pasture lands, as well as channel erosion and sedimentation; and aquatic ecosystem functions.

Typically the available data for catchments (other than heavily instrumented research catchments) is limited to daily rainfall and temperature and, in some cases, stream discharge. Thus the mathematical model most often used is a rainfall-runoff model. Rainfall-runoff models fall into several categories: metric, conceptual and physics-based models. Metric models are typically the most simple, using observed data (rainfall and streamflow) to characterise the response of a catchment. Conceptual models impose a more complex representation of the internal processes involved in determining catchment response, and can have a range of complexity depending on the structure of the model. Physics-based models involve numerical solution of the relevant equations of motion.

The selection of which model to use should be based on the issue(s) being investigated. As more complex questions are asked, more complex models are needed to provide the answers. However, with increasing model complexity comes the cost of increasing uncertainty in the model predictions. The

IHACRES model is a hybrid conceptual-metric model, using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models while at the same time attempting to represent more detail of the internal processes than is typical for a metric model. Figure 1 shows the generic structure of the IHACRES model. It contains a non-linear loss module which converts rainfall into effective rainfall (that portion which eventually reaches the stream prediction point) and a linear module which transfers effective rainfall to stream discharge. Further modules can be added including one which allows recharge to be output. The inclusion of a range of non-linear loss modules within IHACRES increases its flexibility for assessing the effects of climate and land use change. The linear module routes effective rainfall to stream through any configuration of stores in parallel and/or in series. The configuration of stores is identified from the time series of rainfall and discharge but is typically either one store only, representing ephemeral streams, or two in parallel, allowing baseflow or slowflow to be represented as well as quickflow. Only rarely does a more complex configuration than this improve the fit to discharge measurements (Jakeman and Hornberger, 1993).

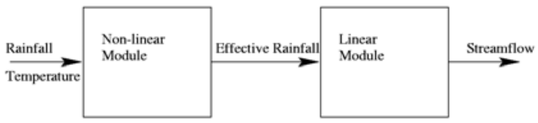

Figure 1. Generic structure of the IHACRES model, showing the conversion of climate time series data to effective rainfall using the Non-linear Module, and the Linear Module converting effective rainfall to streamflow time series.

Various versions of the IHACRES model have also been used to address regionalisation issues (Post and Jakeman, 1996; Sefton and Howarth, 1998, Kokkonen et al, 2001). These issues require methods for estimating the parameters of models from independent means such as landscape attributes rather than directly from rainfall-discharge time series. The parametric efficiency of IHACRES (often about six parameters) lends itself to regionalisation problems, making it easier than complex models to relate its parameters to landscape attributes. The IHACRES model is one of the models to be used by the Top-Down modelling Working Group operating as part of the Prediction in Ungauged Basins initiative (Littlewood *et al*. 2003).

NEW VERSION OF IHACRES

There are a number of reasons for the development of a Java-based version of the rainfall-runoff model IHACRES. This includes several recent developments in the IHACRES model, particularly with the non-linear loss module. One such modification is the development of a catchment moisture deficit (CMD) accounting system which enables a more process-based determination of the partitioning of rainfall to discharge and evapotranspiration (Croke and Jakeman, 2004). Other enhancements include simulating the effects of retention storages such as farm dams on stream discharge (Schreider *et al*. 1999) as well as the interaction between groundwater recharge and streamflow by linking a physics-based groundwater discharge model (Sloan, 2000) with the IHACRES model (Croke *et al.* 2002). The groundwater version of the model was used to assess groundwater recharge in the Jerrabomberra Creek catchment, ACT (Croke *et al*. 2001). These developments have improved the potential of IHACRES to model the effects of land use change on catchment response (e.g. Dye and Croke, 2003), as well as inferring the response of ungauged catchments.

Further advances in the IHACRES model have been made in the method of calibration. In addition to the current simple refined instrumental variable (SRIV) method of parameter estimation (e.g. Jakeman et al., 1990), a method based on estimating hydrographs directly from streamflow data without the need for rainfall data has been developed (Croke, 2004). This enables higher resolution streamflow data to be used, reducing the loss of information which occurs when data is binned to a daily timestep. In addition, this calibration method reduces the number of parameters that need to be estimated within the model, thus reducing the parameter uncertainty while at the same time reducing the time required to calibrate the model. Another facility being developed is the capacity to use PEST, a powerful parameter estimation package which is flexible enough to be applied to a wide range of functions including any new class of non-linear loss modules. In order to use this model independent parameter estimation software, the IHACRES model needs to be able to be run from the command line.

Non-linear modules

Currently, an adaptation of the non-linear module of Ye *et al.* 1997 has been coded within IHACRES_v2.0, with the effective rainfall u_k given by:

$$u_k = \left[c\left(\phi_k - l\right)\right]^p r_k \qquad (1)$$

where r_k is the observed rainfall, *c, l* and *p* are parameters (mass balance, soil moisture index threshold and non-linear response terms, respectively), and ϕ_k is a soil moisture index given by:

$$\phi_k = r_k + \left(1 - 1/\tau_k\right)\phi_{k-1} \qquad (2)$$

with the drying rate τ_k given by:

$$\tau_k = \tau_w \exp\left(0.062 f\left(T_r - T_k\right)\right) \qquad (3)$$

where τ_w, *f* and T_r are parameters (reference drying rate, temperature modulation and reference temperature, respectively). This formulation enables the gain of the transfer function to be directly related to the value of the parameter *c*, thus simplifying model calibration. This version of the model is more general than the version used within the IHACRES_PC model (Littlewood et al. 1997) which can be recovered by setting parameters *l* to zero and *p* to one (with the soil moisture index in the original model given by $s_k = c\phi_k$). This version of the non-linear module is described in detail in Jakeman *et al.* (1990) and Jakeman and Hornberger (1993). Examples of studies that have used this version of IHACRES (with minor modifications to the Equation 3) can be found in Hanson et al. (1996), Post and Jakeman (1999), Schreider et al. (1996) and Ye et al. (1997).

Use of the Java Programming Language

The choice of using the Java programming language was based on a variety of factors. Advantages associated with Java include: platform independence, advanced high-level user interface tools and support for modern software engineering. Some of these advantages come at a cost. After analysing the requirements of IHACRES_v2.0 and the characteristics of the Java programming language, compared to other programming languages, it was decided that Java was the most appropriate choice.

A disadvantage associated with using Java is that it is potentially slower than other languages due to its platform independence. Generally a program that is native to a particular platform will be faster than the equivalent Java program. In choosing Java it was decided that the significant advantage of platform independence outweighed this disadvantage. This may not have been the case with models that are more computationally demanding than IHACRES.

Design

The object-oriented paradigm has been applied throughout the design of the new Java-based IHACRES. The key concepts associated with this paradigm are information hiding, reuse and an object-oriented view of the problem domain (Behforooz and Hudson, 1996). Information hiding, or encapsulation, is a design strategy that promotes hiding the details of implementation within the design envelope of a software component. The object-oriented paradigm encourages the reuse of code, and this has many benefits. Viewing the problem domain from an object-oriented perspective makes the design easier to understand: software objects correspond to entities from the problem domain, and their relationships are represented explicitly. The application of this paradigm has increased the quality of IHACRES_v2.0.

VISUALISATION OF DATASETS AND RESULTS

In order to visualise data, the new Java-based version of IHACRES makes use of the VisAD library. VisAD (Hibbard, 1998) is a Java component library for interactive visualisation and analysis of numerical data. The library is available under the Lesser General Public License (LGPL), which allows the library to be used in commercial applications so long as certain conditions are satisfied. Using VisAD it has been possible to create very sophisticated interactive visualisations of data within IHACRES_v2.0 with a minimum amount of effort. The visualisation of data is very important for the calibration and interpretation of models like IHACRES_v2.0 where it is necessary for users to be able to view effective representations of data in order to make appropriate decisions.

A number of changes have been made to the objective functions used in IHACRES_v2.0. The lag 1 correlation coefficients U1 (correlation coefficient of the lagged effective rainfall and model error) and X1 (correlation coefficient of the lagged modelled streamflow and the model error) have been normalised correctly (e.g. a value of +1 corresponds to perfect correlation) to aid in interpretation of these values. Also, a number of objective functions have been added. These are based on the Nash-Sutcliffe model efficiency indicator:

$$R^2 = 1 - \frac{\sum_i \left(Q_{o,i} - Q_{m,i}\right)^2}{\sum_i \left(Q_{o,i} - \bar{Q}_o\right)^2} \qquad (4)$$

with the observed flow Q_o, and modelled flow Q_m replaced with the square root, logarithm and inverse of the flow. To avoid numerical errors with the logarithmic and inverse versions, the 90% flow exceedence value (ignoring timesteps with no flow) was added to Q_o. These shift the weighting of the objective function progressively from the flow peaks to low flows.

FUNCTIONALITY

In designing the user interface for IHACRES_v2.0 the core functionality was broken up into three areas: data, calibration and simulation. A typical user of IHACRES_v2.0 will initialise the data within the software using the data panel. Then they will generate calibrations of the IHACRES mathematical model using this data via the calibration panel. Finally they will simulate time series of discharge (and perhaps other variables depending on the model modules invoked) using the (input) data and calibrations.

Data Panel

The data panel indicates to the user the state of all the data sets within the system; a data set is basically a time series of some type of data, observed rainfall or discharge for example. This panel enables the basic climate and streamflow data to be imported into IHACRES_v2.0, with a range of commonly used units being available. In addition, the catchment area is also specified at this stage.

Calibration Panel

The calibration panel allows the user to define one or more calibration periods (see Figure 2). A calibration period is the range of data that will be used to calibrate the model. The user has the option of displaying each data set within the system, as well as a moving average runoff coefficient. The user can use the range slider to select a particular range to display on the charts; alternatively, they can type in dates or timestep numbers. Defining multiple calibration periods allows different data ranges or calibration techniques to be compared.

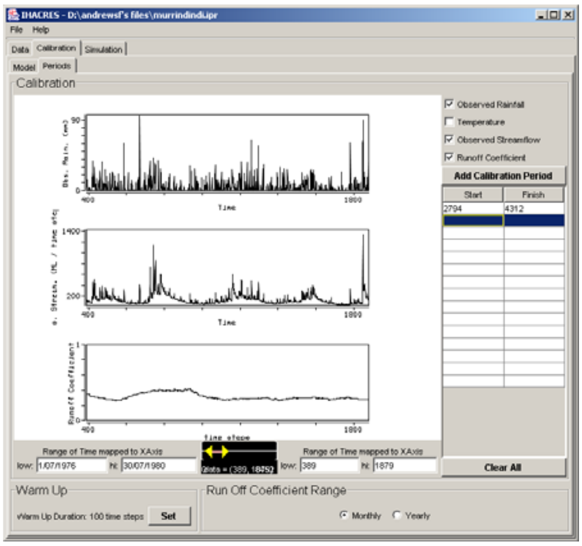

Figure 2. Calibration period selection window

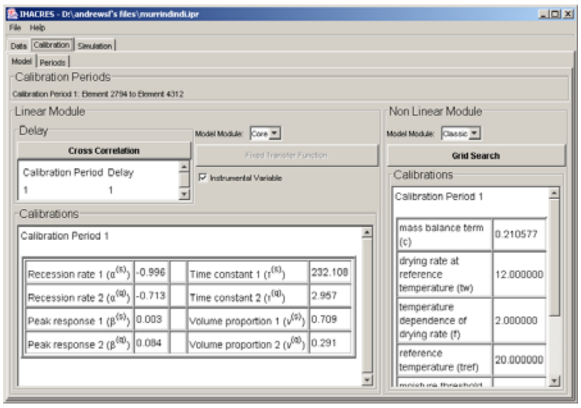

Figure 3. Calibration window showing calibrated parameter values

The calibration panel allows the user to select from the available modules depending on the current task, and also allows the user to access particular calibrators for calibrating the selected modules. The calibration panel shows the current calibration state of the software in the form of a set of parameter values for each non-linear and linear module calibration. An additional panel shows the delay between rainfall and streamflow, which can be determined using the Cross Correlation tool. This tool determines the auto-correlation of rainfall and streamflow as well as the cross correlation of these data sets for each calibration period. The delay is then determined from the cross correlation function peak, although the user is given the option to modify it.

Currently only the Grid Search calibrator is implemented for the Non-linear module, and the Fixed and en-bloc SRIV calibrators for the linear module. The Fixed calibrators simply allow the user to enter in parameter values directly. The Grid Search calibrator searches a defined uniform sample of parameter values for the optimal set, producing a list of model statistics for each point in the search. The user can then select the optimal set based on the displayed statistics, as well as plots of the observed and modelled flow for the calibration period.

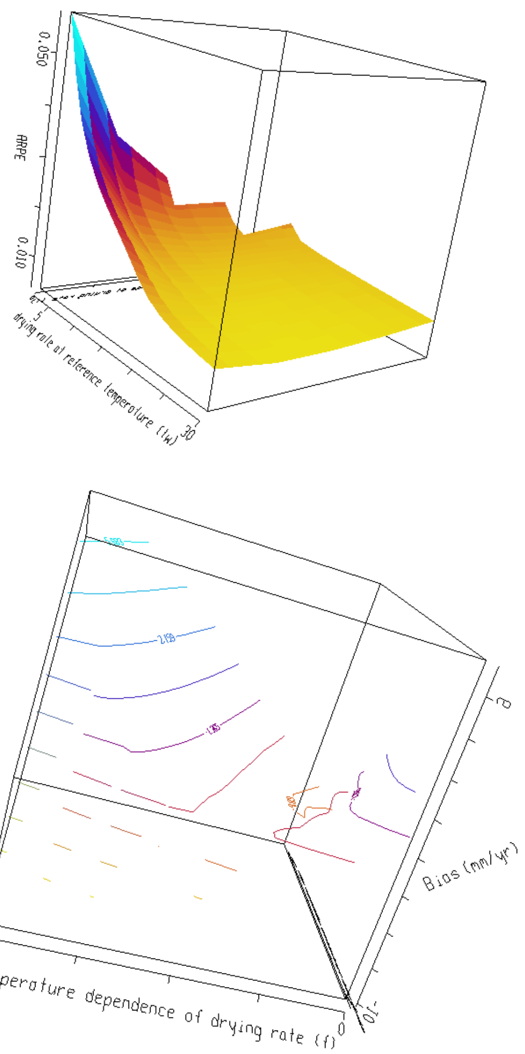

Figure 4. Examples of 3-D visualisation of results from calibration grid search

To aid with selection of an optimal set of parameter values, a variety of charting tools are available. 3-D shaded surfaces and contour plots can be generated (e.g. Figure 4) as well as 2-D contour and line plots (e.g. Figure 5).

Once the user has specified one or more calibrations, where a calibration is combination of a non-linear module calibration and a linear module calibration, a simulation can be run through the simulation panel.

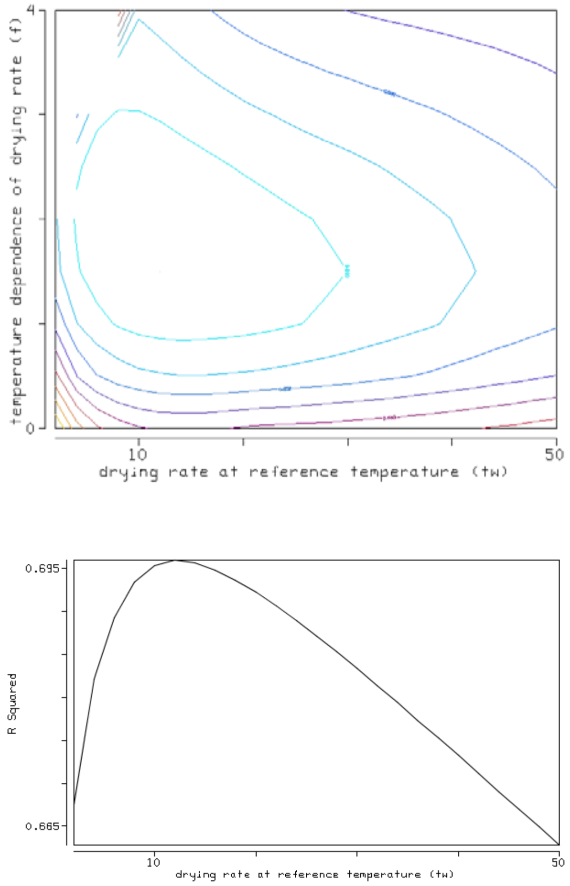

Figure 5. Example of 2-D plots of calibration results, showing variation of R^2 with τ_w.

Simulation Panel

The simulation panel allows the user to run simulations and analyse the data generated by simulations. Once a simulation has run, the user is able to plot the simulation results, or export the results in a comma separated ASCII file. The data generated by a simulation includes ‘extra’ data produced by particular modules, for example the Catchment Moisture Deficit non-linear module generates a time series of catchment moisture deficit values for each simulation run.

APPLICATION OF MODEL

The IHACRES_v2.0 software has been used to model streamflow in the Murrindindi River catchment (104km^2) in Victoria, Australia. This is a small forested catchment in the southern Goulburn River basin. Figure 6 shows the cross correlation of streamflow with rainfall, along with the autocorrelations of rainfall and streamflow. The comparison of modelled and measured streamflow for this catchment is shown in Figure 7. The modelled flow reproduces the observed flow well, except for extreme events, where the surface runoff is underestimated.

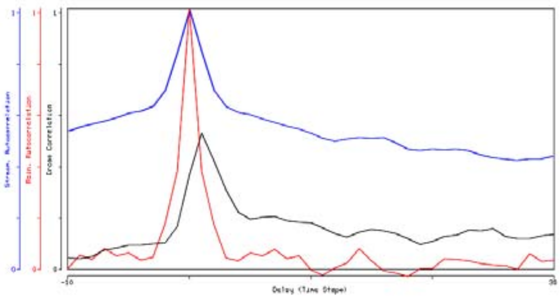

Figure 6. Cross correlation delay calibrator. Black line is the cross correlation of streamflow and rainfall timeseries, red line is the autocorrelation of rainfall and blue line is the autocorrelation of streamflow.

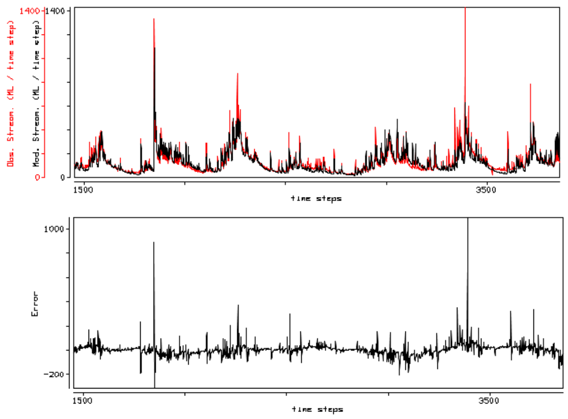

Figure 7. Modelled and observed streamflow for Murrundindi River catchment, Victoria, Australia.

PLANNED FUTURE DEVELOPMENTS

There are a number of enhancements planned for the new version of IHACRES. These include:

- The CMD version of the non-linear module
- Adding flow duration plotting capability
- Introducing objective functions based on the flow duration curve
- Regressive form of the SRIV algorithm
- Direct estimation of the unit hydrograph response curve (Croke, 2004)
- Baseflow filtering tool using Lyne-Hollick, Boughton, IHACRES and a generalised constrained filter (Croke *et al.* 2002)
- Spectral analysis tools, including a Fourier transform tool to enable estimation of the unit hydrograph response using Fourier decomposition of streamflow and rainfall (Croke *et al.* 2000)
- Sensitivity analysis tool

CONCLUSION

The IHACRES_v2.0 software is a considerable enhancement of the IHACRES_PC software. The software can be used on any platform that has the appropriate Java runtime environment. In addition, the functionality of the software has been increased through the inclusion of additional non-linear modules and alternative calibration techniques, as well as improved visualisation of data and modelled results.

ACKNOWLEDGMENTS

The authors wish to thank Ian Littlewood for discussions on the development of this version of IHACRES, and the beta testers for help in testing the software.

REFERENCES

Behforooz, A. and F.J. Hudson, 1996, Software Engineering Fundamentals, Oxford University Press, United States of America.

Croke, B., N. Cleridou, A. Kolovos, I. Vardavas and J. Papamastorakis, Water resources in the desertification-threatened Messara-Valley of Crete: estimation of the annual water budget using a rainfall-runoff model, Environmental Modelling and Software, 15 (2000), 387–402.

Croke, B.F.W., 2004, A technique for deriving the average event unit hydrograph from streamflow-only data for quick-flow-dominant catchments, in preparation.

Croke, B.F.W. and A.J. Jakeman, 2004, A Catchment Moisture Deficit module for the IHACRES rainfall-runoff model, *Environmental Modelling and Software*, 19, 1–5.

Croke, B.F.W., A.B. Smith and A.J. Jakeman (2002) A One-Parameter Groundwater Discharge Model Linked to the IHACRES Rainfall-Runoff Model. In: A. Rizzoli and A. Jakeman (eds), Proceedings of the 1st Biennial Meeting of the International Environmental Modelling and Software Society, University of Lugano, Switzerland, Vol I, 428–433.

Croke, B.F.W., W.R. Evans, S. Yu. Schreider and C. Buller, 2001. Recharge estimation in the Jerrabomberra Creek catchment, ACT. *MODSIM2001*, Canberra, ACT, December 10–13, 2001.

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

Hansen, D. P., W. Ye, A.J. Jakeman, R. Cooke and P. Sharma, 1996, Analysis of the effect of rainfall and streamflow data quality and catchment dynamics on streamflow prediction using the rainfall-runoff model IHACRES, *Environmental Software*, 11, 193–202.

Hibbard, W., 1998, VisAD: Connecting people to computations and people to people, *Computer Graphics* 32, 10–12.

Jakeman, A. J., and G. M. Hornberger, How much complexity is warranted in a rainfall-runoff model?, *Water Resources. Research*, 29, 2637–2649, 1993.

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

Kokkonen, T., A.J. Jakeman and P.C. Young, 2001, Predicting daily flows in ungauged catchments — model regionalisation from catchment descriptors at Coweeta, *Hydrological Processes*, in review.

Littlewood, I.G., B.F.W. Croke, A.J. Jakeman and M. Sivapalan, 2003, The role of 'top-down' modelling for Prediction in Ungauged Basins (PUB), *Hydrological Processes*, 17, 1673–1679.

Littlewood, I.G., K. Down, J.R. Parker and D.A. Post, *'IHACRES — Catchment-scale rainfall-streamflow modelling (PC version) Version 1.0 — April 1997'*, The Australian National University, Institute of Hydrology and Centre for Ecology and Hydrology.

Post, D.A. and A.J. Jakeman, 1996, Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments, *Hydrological Processes*, 10, 877–892.

Post, D.A. and A.J. Jakeman, 1999, Predicting the daily streamflow of ungauged catchments in S.E. Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model, *Ecological Modelling*, 123, 91–104.

Schreider S.Yu., A.J. Jakeman, R.A. Letcher, S.G. Beavis, B.P. Neal, R.J. Nathan, N. Nadakumar and W. Smith, 1999, Impacts and Implications of Farm Dams on Catchment Yield, iCAM working paper 1999/3. ISSN 1442–3707.

Schreider, S. Y., A.J. Jakeman and A.B. Pittock, 1996, Modelling rainfall-runoff from large catchment to basin scale: The Goulburn Valley, Victoria, *Hydrological Processes*, 10, 863–876.

Sefton, C.E.M. and S.M. Howarth, 1998, Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales, *Journal of Hydrology*, 211, 1–16.

Sloan, W.T., 2000, A physics-based function for modelling transient groundwater discharge at the watershed scale, *Water Resources Research*, 36, 225–241.

Ye, W., B. C. Bates, N. R. Viney, M. Sivapalan and A. J. Jakeman, 1997, Performance of conceptual rainfall-runoff models in low-yielding ephemeral catchments, *Water Resources Research*, 33, 153-16.