Precipitation - Runoff Model Calibration On A Sub-daily Time Step In The Upper Murray Basin

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Abstract This paper describes the results of rainfall runoff modelling for ten catchments in the Upper Murray Basin (Basin 401) of the Murray Darling Drainage Division (MDDD), Australia. The outflows of these catchments are used by the Murray Darling Basin Commission for operational management of the Hume and Dartmouth Lakes, two of Australia's four largest reservoirs. Previous results (Schreider *et al.*, 1996a,b,c and 1997) have demonstrated that the conceptual, lumped parameter, rainfall-runoff model IHACRES provides a good approximation to the daily measured flow in several Basins of the MDDD. The major aim of the research described in this paper is the identification of models based on a shorter four hourly sampling interval. In a comparison paper (Young *et al.*, 1997) these identified models are used in a Kalman Filter-based forecasting framework to allow real-time forecasts of streamflow in these catchments.

1. INTRODUCTION

The IHACRES model applied here for prediction of runoff is a hybrid metric-conceptual model based on the Instantaneous Unit Hydrograph (IUH) technique. The IHACRES model contains two modules: a non-linear loss module allowing for calculation of the effective (or excess) rainfall from the measured precipitation and temperature data series; and a linear transfer function module representing the streamflow as a recursive linear combination of the antecedent values of streamflow and effective rainfall. This method is based on a transfer function representation of the total streamflow response computed as a linear convolution of the IUH (hydrograph of direct runoff resulting from one unit of effective rainfall generated uniformly over a catchment area with instantaneous duration) with rainfall excess or effective rainfall. It is partly metric in the sense that measured precipitation-discharge observations are used to infer the configuration and number of stores used to represent the linear convolution. The lumped parameter rainfall-runoff model IHACRES has been tested successfully in several regions worldwide for catchments of different sizes and under different climate conditions (e.g. Jakeman *et al.*, 1990, 1993; Jakeman and Hornberger, 1993; Ye *et al.*, 1995, Hansen *et al.*, 1996; 1997; Schreider *et al.*, 1995, 1996a,c; Post *et al.*, 1996).

The advantage of applying the conceptual model is its relative simplicity, in terms of the limited number of parameters to be optimised (only six in the case of the IHACRES model). Potentially, relationships can also be developed between these parameters and landscape characteristics of the catchments considered (Post and Jakeman, 1996; Sefton and Boorman, 1997).

2. DESCRIPTION OF THE UPPER MURRAY BASIN

A description of the Upper Murray Basin (Hume Catchment) is provided in Schreider *et al.* (1996b), however some basic information is presented here for convenience. The Upper Murray Basin is located in the south-eastern part of the MDDD and covers 15,300 km^2 of territory in the states of Victoria (the Mitta-Mitta River catchment and left bank of the Murray River with total area of 10,000 km^2) and New South Wales (Figure 1). River flows are regulated by the Hume and Dartmouth reservoirs operated by the Murray-Darling Basin Commission (MDBC). The River Murray Water Agreement regulates redistribution of water in this Basin between the states of Victoria and New South Wales. Climate characteristics of the Basin and physiography of its Victorian part are described in Schreider *et al.* (1996b). Lake Dartmouth, the largest reservoir in the state of Victoria, with about 4,000,000 ML capacity is located in the middle of the Mitta-Mitta catchment. The right bank of the Murray catchment belongs to the New South Wales part of the Basin. The largest water contributors in this area are the Upper Murray River at Biggara (1,165 km^2) and the Tooma River catchment at Pine Grove (1,819 km^2). These two catchments gain water from the western slopes of the Snowy Mountains, which is the highest region in Australia (Mt. Kosciusko 2228 m AHL). The Hume reservoir with a capacity over 3,000,000 ML is located in the north-western part of the Basin. The outlet of an inter-basin water transfer via the Snowy Mountains Hydroelectric Scheme, providing 580,000 ML annually on average, is located in this part of the Basin. The Jingellic Creek catchment is located in the north of the New South Wales part of the Basin.

Land use in the Basin is not very intense: about 80% of its area is forested, although all the major valleys which lie in its north have been cleared for agriculture (Water Victoria, 1989). While water use in this Basin is small (4,830 ML per year on average), it is one of the major contributors of water resources in the MDDD.

Streamflow information from the catchments selected for analysis here is used by the MDBC for calculating inlet flows for the Hume and Dartmouth reservoirs. A list of these catchments, their mean annual discharge and areas, is presented in Table 1.

Table 1: The catchments of the Upper Murray Basin selected for consideration.

Station number	River and station location	Mean annual discharge (ML)	Area (km^2)
401203	Mitta-Mitta River at Hinnomunjie	475,000	1533
401230	Corryong Creek	159,000	387
401220	Tallangatta Creek at McCallums	71,900	464
401229	Cudgewa Creek at Berringama	102,000	350
401012	Murray River at Biggara	532,000	1165
401217	Gibbo River at Gibbo	135,000	389
401210	Snowy Creek at Granite Flat	195,000	407
401013	Jingellic Creek at Jingellic	66,000	328
401014	Tooma River at Pine Grove	442,000	1819
401216	Big River U/S of Joker Ck	231,000	356

3. THE MODEL AND DATA

3.1 The model

A description of the data-based, lumped parameter conceptual model IHACRES is provided in Jakeman *et al.* (1990), Jakeman and Hornberger (1993). The model consists of two components: a non linear module transforming the measured precipitation into effective (or excess) rainfall; and a linear transfer function module computing the modelled streamflow as a linear combination of antecedent values of streamflow and effective rainfall. Here the conception of two reservoirs connected in parallel (quick and slow components) has been identified as most statistically appropriate (see also Young, 1992).

The non-linear loss module is used to account for the effect of antecedent weather conditions on both the current status (s_k) of soil moisture and vegetation conditions; and for evapo-transpiration effects. Here the effective rainfall u_k is calculated from the measured rainfall r_k and temperature t_k in the catchment area by the formulae:

$$u_k = r_k\,(s_k + s_{k-1})/2$$

$$s_k = r_k/c + (1 - 1/t_w(t_k))\,s_{k-1}$$

$$t_w\,(t_k) = t_w\,exp(20f - t_k f)$$

Here, the constant c is calculated so that the volume of effective rainfall is equal to the total streamflow for the calibration period; and the parameters t_w and f are optimised.

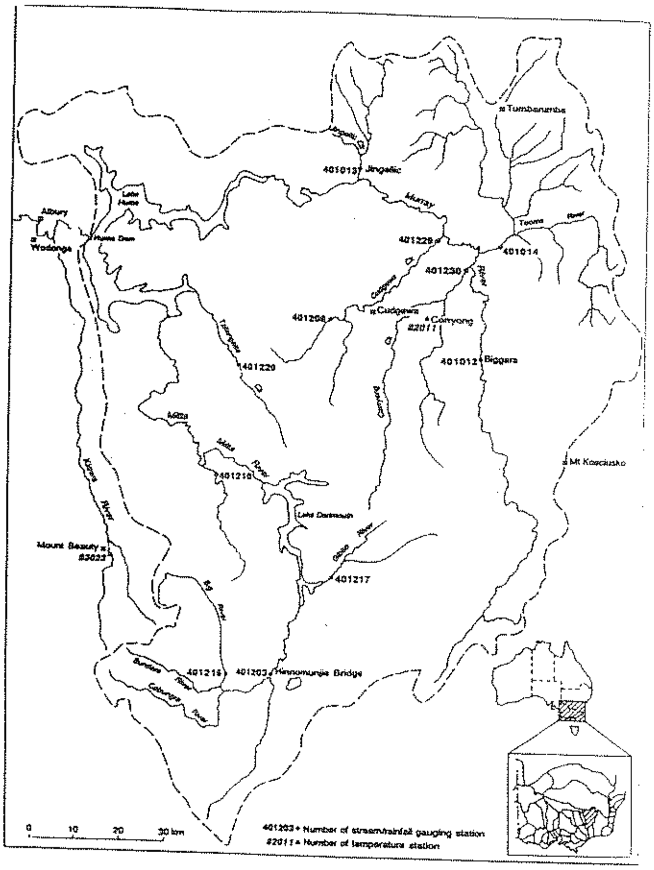

Figure 1: River network, meteorological and discharge stations for the catchments considered in the Upper Murray Basin.

This linear module represents the modelled value of streamflow y_k as a recursive relationship between antecedent values of modelled flow and effective (excess) rainfall. In the case of the two reservoir structure it is a sum of modelled values of quick and slow flow components. This module can be represented in a single, discrete-time equation form as:

$$y_k = -a_1 y_{k-1} - a_2 y_{k-2} + b_0 u_{k-d} + b_1 u_{k-d-1}$$

The four parameters of this linear module are estimated using the Simple Refined Instrumental Variable (SRIV) technique (e.g. Jakeman *et al.*, 1990; Young, 1985, 1992) and then converted into the parameters a_q, a_s, b_q, b_s of the quick and slow flow compartments (see Jakeman *et al.*, 1990 and Young *et al.*, 1997).

Some of the catchments considered have headwaters located in the upper part of the Victorian Alpine region and are considerably snow-affected. A snow melt/accumulation module, based on the empirical degree-day approach (Schreider *et al.*, 1996b), is an adjunct to IHACRES for streamflow modelling in these catchments.

3.2 Data considerations

Some particulars concerning the changes in methodology when modelling on a 4-hourly step, rather than daily, should be mentioned here. Firstly, the snow melt/accumulation module developed for a daily time step cannot be applied directly for the 4-hourly analysis, because of lack of empirical data (degree-day coefficients, probabilities of precipitation falling as snow etc.) at such a fine temporal resolution. Consequently, the snow melt/accumulation module was modified for application from a daily to a sub-daily step using a linear regression of melt water excess (or accumulated water deficit) against temperature. This linear regression was established for daily data, estimated by the spatially distributed snow melt/accumulation model, and than transferred to the 4-hourly data. Despite this modification, it was not applied for streamflow forecasting (Young *et al.*, 1997), because it provided little advantage for this application (see later). It could be used for the simple predictive modelling of 4-hourly streamflow time series and it provided some benefit (in terms of Nash - Sutcliffe (1970) efficiency) in such prediction: i.e. efficiency was improved compared with the results obtained for the IHACRES model applied alone, without this module, for streamflow prediction.

Secondly, only the minimum and maximum daily temperature data are recorded for the region considered, so the 4-hourly temperature data were interpolated from minimum and maximum daily temperature records of the Corryong and Mt Beauty meteorological stations (82011 and 83023, Australian Bureau of Meteorology) using the sine-logarithmic algorithm developed by Linvill (1990). This is based on the assumption of a sinusoidal approximation to temperature during the daytime with a maximum at 2 hours after the solar noon and a logarithmic decrease of temperature from sunset to the minimum at sunrise. These temperature data were used for streamflow modelling in every catchment of the Upper Murray Basin.

The 4-hourly streamflow and rainfall data for the Victorian and New South Wales parts of the Basin were provided by Thiess Environmental Services and the NSW Department of Land and Water Conservation, respectively. The rainfall data were registered at the same sites that the corresponding streamflow data were recorded, except for the case of Tallangatta Creek, which is specified below.

4. INVENTORY OF THE STREAMFLOW MODELLING RESULTS

The results of the model calibrations are presented in Table 2 and the calibration procedure for the Tallangatta Creek catchment is described in more detail below. Also, the issue of the snow melt/accumulation model applicability is discussed, using the Snowy Creek catchment as an example.

4.1 Tallangatta Creek

Calibration on a 4-hourly time step was carried out for the snow-free catchment of Tallangatta Creek, where such data are available for the McCallums station (N 401230). 4-hourly precipitation data were taken from the Granite Flat (401210) station located about 25 km to the south of the stream gauging station (the same location as stream gauging station N 401210). The 4-hourly streamflow data were available for the period 1/01/1991-8/02/1995. Although the rainfall data were recorded for the same period, only two relatively long periods of continuous recording exist: 3/01/1991-4/09/1991 and 2/06/1993-14/05/1994. This lack of measurements does not allow for calibration of the model outside these time intervals.

The models were calibrated over two different periods: 360, 4-hourly time steps (90 days); and 1800, 4-hourly steps (300 days). The main problem is related to the poor quality of streamflow records during Summer: for some time intervals with no rainfall recorded, the streamflow records are constant, with no decay. However, the calibration results obtained for the winter periods describe the streamflow processes well. Figure 2 presents the calibration results obtained for the 90-day period of 5/07/1993-3/09/1993, with an efficiency statistic $E = 0.871$. The simulation results for this model over the 300-day period (5/07/1993-1/05/1994) are presented in Figure 3, where the efficiency statistic is $E = 0.868$. The calibration results obtained for this 300-day period gave similar results, with $E = 0.878$. In both cases, the low flows in the Summer period are approximated poorly. This is related to the quality problem associated with the summer flow data, as mentioned above.

Table 2: The results of the 4-hourly IHACRES calibration for the Upper Murray Basin catchments.

Station number	River and station location	Observation period	Efficiency E
401203	Mitta-Mitta River at Hinnomunjie	3/01/91-14/02/95	
401230	Corryong Creek	22/08/93-5/03/96	0.888
401220	Tallangatta Creek at McCallums	5/07/91-8/02/95	0.871
401229	Cudgewa Creek at Berringama	17/12/93-5/03/96	0.640
401012	Murray River at Biggara	2/09/93-30/04/96	0.928
401217	Gibbo River at Gibbo	3/01/91-19/12/95	0.730
401210	Snowy Creek at Granite Flat	3/01/91-5/03/96	0.887
401013	Jingellic Creek at Jingellic	3/01/91-14/02/95	0.664
401014	Tooma River at Pine Grove	11/09/93-30/04/96	
401216	Big River U/S of Joker Ck	18/03/93-22/06/9	0.679

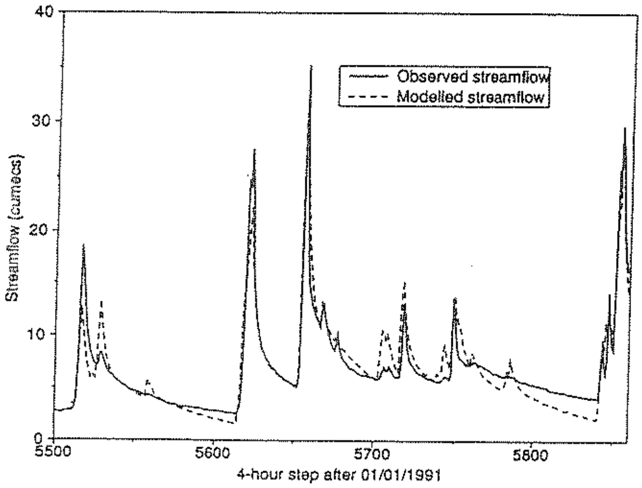

Figure 2: Observed (solid line) and modelled (dashed line) streamflow (cumecs) for the Tallangatta Creek catchment (calibration over a 90 day winter period).

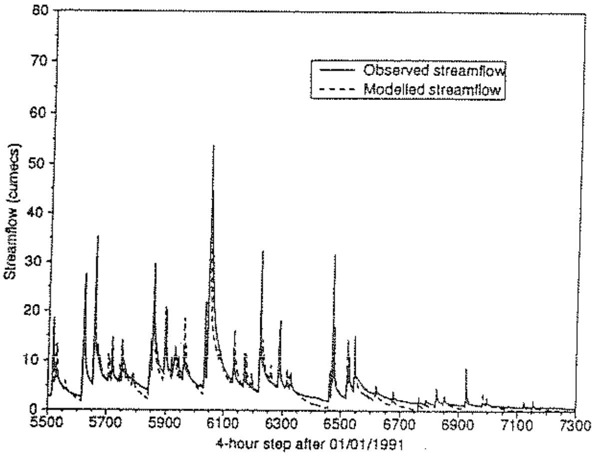

Figure 3: Observed (solid line) and modelled (dashed line) streamflow (cumecs) for the Tallangatta Creek catchment (simulation over a 300 day period).

The streamflow series obtained by simulation over the period 5/07/1993-1/05/1994, on the 4-hourly time step, were aggregated to a daily time step and then the daily simulation, based on the calibrated 4-hourly model converted to a daily basis, was implemented. The efficiency statistic is similar here with $E = 0.899$, which is a much higher value than is usually obtained for model simulations.

4.2 Corryong and Jingellic Creek

Other examples of model calibration are given for the Corryong and Jingellic Creek catchments. As the period when streamflow and rainfall data are available simultaneously for Corryong Creek is relatively short, only one calibration period with a high value of $E = 0.844$ for the efficiency statistic was possible. The Jingellic Creek catchment was calibrated with poorer convergence, giving an efficiency value of only $E = 0.664$. This is the worst calibration obtained for all ten catchments and can be explained only by the poor quality of the precipitation and streamflow data recorded for this catchment. The catchment area is relatively small (328 km^2) compared with other catchments of the Basin and the poor results cannot be explained by snow melt/accumulation processes as, for example, in the case of the Big River, where the calibration efficiency is also low (Table 2).

4.3 Cudgewa Creek

Modelling of the Cudgewa creek catchment provided difficulties related mainly to the fluctuation of streamflow within the daily period (maximum flow at 4 pm, minimum flow at 8 am). These fluctuations are explained by a sensitivity of the gauging instruments to the daily temperature fluctuations (Thiess Environmental Services, personal communication). However, the nature of these fluctuations is not clear enough because they are not observed for some catchments of the Basin, even those located rather close to the Cudgewa Creek catchments and operated by the same organisation (e.g. the Tallangatta Creek catchment). The calibration result obtained for this catchments is also poorer than those for other catchments, except Jingellic Creek. However, the efficiency value, $E = 0.640$, is quite acceptable given the instrumentally induced problems.

4.4 Snowy Creek

The Snowy Creek catchment can be used to illustrate the comparative performance of the IHACRES model with and without a snow melt/accumulation module. Similar comparative results have been found for the other snow-affected catchments in the Upper Murray Basin (the Mitta-Mitta, Murray at Biggara, Tooma and Big Rivers).

The model calibration obtained with no snow melt/accumulation module is presented in Figure 4. The efficiency statistic is 0.887 compared with 0.902 for the model applied with the snow module, demonstrating that little advantage appears to be gained by including the module.

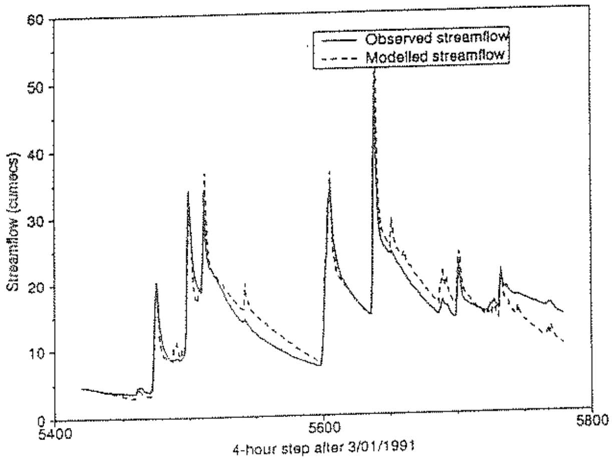

Figure 4: Observed (solid line) and modelled (dashed line) streamflow (cumecs) for the Snowy Creek catchment (no snow melt/accumulation module applied).

Some problems related to the applicability of the snow melt/accumulation module should be mentioned here. Firstly, during the winter period, where the calibration period was selected, the model exhibits diurnal fluctuations in flow, explained by the daily temperature cycle: there is extensive snow melt during the day time and a reduction of these processes at night. However, this process is not reflected in the measured streamflow data. An explanation for this phenomena is probably the smoothing of the snow melt/accumulation processes at the 4-hourly scale by the transportation of flow from all contributing parts of the catchment, not only from the upper snow-affected part. Secondly, an instrumentally induced periodical component of streamflow, as encountered in the Cudgewa Creek, also exists in Snowy Creek. The fluctuation of streamflow within a daily period (maximum flow at 4 pm, minimum flow at 4 am) cannot be explained by daytime snow melt processes because they are especially strong during summer periods, when snow cover in the catchment does not exist but when the gauging instruments are more sensitive to the temperature variations because the temperature is high.

These problems, coupled with the poor results discussed above, are the main reasons why the snow melt/accumulation module has not been used in the initial work on operational streamflow forecasting in the catchments of this region, as reported in the companion paper (Young *et al.*, 1997).

4.5 Mitta-Mitta and Tooma Rivers

The cases of the Mitta-Mitta and Tooma Rivers should be mentioned here. No model convergences were obtained for these two catchments on a 4 hourly time step. The possible explanation is their large areas: 1,533 km^2 and 1,819 km^2, respectively. However, the model parameters obtained for the Big River catchment, scaled according to differences in their mean annual discharge, were used in these two catchments for the forecasting stage of the algorithm (Young *et al.*, 1997). The model calibrated for Big River was selected because of its similarity (in terms of landscape and vegetation) to these two catchments. The argument for such a solution comes from the results of Post and Jakeman (1996) and Post *et al.* (1996), who provide relationships between catchment landscape and vegetation characteristics and the IHACRES model parameters.

5. DISCUSSION AND CONCLUSIONS

The conceptual rainfall-runoff model IHACRES has been calibrated for ten catchments in the Upper Murray Basin using a 4-hourly time step for input and output time series. This is the first application of IHACRES on a sub-daily time step at the scale of an entire Basin. The results of the present work are employed for the operational streamflow forecasting algorithm described in the companion paper, Young *et al.* (1997).

6. REFERENCES

Hansen D.P., Jakeman, A.J., Kendall, C. and Gu, W. Identification of Internal Flow Dynamics in Two Experimental Catchments. *Mathematics and Computers in Simulation*, 43 (3-6), pp. 367-375, 1997.

Hansen, D.P., Ye, W., Jakeman, A.J., Cooke, R. and Sharma, P. Analysis of the Effect of Rainfall and Stramflow Data Quality and Catchment Dynamics on Streamflow Prediction using the Rainfall-Runoff Model IHACRES. Environmental Software, 11, (1-3), pp. 193-202, 1996.

Jakeman, A.J., Littlewood, I.G and Whitehead, P.G., Computation of the Instantaneous Unit Hydrograph and Identifiable Component Flows with Application to Two Small Upland Catchments. *Journal of Hydrology*, 117, pp. 275-300, 1990.

Jakeman, A.J., Chen, T.-H., Post, D.A., Hornberger, G.M., Littlewood, I.G. and Whitehead, P.G. Assessing uncertainties in hydrological response to climate at large scale. Symposium on *Macroscale Modelling of the Hydrosphere*, Joint IAMAP-IAHS Scientific Assembly, Yokohama, Japan, July 11-23. IAHS Publication No. 214, W.B. Wilkinson (ed.), pp. 37-47, 1993.

Jakeman, A.J. and Hornberger, G.M. How Much Complexity is Warranted in a Rainfall-Runoff Model?, *Water Resources Research*, 29(8), pp. 2637-2649, 1993.

Linvill, D.E., Calculating Chilling Hours and Chill Units from Daily Maximum and Minimum Temperature Observations. *HortScience*, 25(1), pp. 14-16, 1990.

Nash, J.E. and Sutcliffe, J.V., River Flow Forecasting Through Conceptual Models, Part I - A Discussion of Principles. *Journal of Hydrology*, 10, pp. 282-290, 1970.

Post, D.A. and Jakeman, A.J., Relationships Between Catchment Attributes and Hydrological Response Characteristics in Small Australian Mountain Ash Catchments. *Hydrological Processes*, 10(6), pp. 877-892, 1996.

Post, D.A., Jakeman, A.J., Littlewood, I.G., Whitehead, P.G. and Jayasuriya M.D.A., Modelling Land Cover Induced Variations in Hydrologic Response: Piccaninny Creek, Victoria. *Ecological Modelling*, 86, pp. 177-182, 1996.

Schreider, S.Yu., Jakeman A.J., Falkland, A. and Knee, R., Streamflow prediction for the Queanbeyan River at Tinderry. *Environment International*, 21(5), pp. 545-550, 1995.

Schreider, S.Yu, Jakeman, A.J. and Pittock A.B., Modelling Rainfall-Runoff from Large Catchment to Basin Scale: the Goulburn Valley, Victoria. *Hydrological Processes*, 10(6), pp. 863-876, 1996a.

Schreider, S.Yu., Whetton, P.H., Jakeman, A.J., Pittock, A.B., and Li, J. Runoff Modelling for Snow-Affected Catchments in the Australian Alpine Region, 1996b, *CRES Working Paper*, ANU 1996/5, Canberra, 26 pp. Also *Journal of Hydrology* (in press .

Schreider, S.Yu., Jakeman, A.J., Pittock, A.B. and Whetton, P.H., Estimation of Possible Climate Change Impacts on Water Availability, Extreme Flow Events and Soil Moisture in the Goulburn and Ovens Basins, Victoria. *Climatic Change*, 34, pp. 513-546, 1996c.

Schreider, S.Yu., Jakeman, A.J, Dyer, B.G. and Francis, R.I., A Combined Deterministic and Self-Adaptive Stochastic Algorithm for Streamflow Forecasting with Application to Catchments of the Upper Murray Basin, Australia. *Environmental Modelling and Software*, 12(1), pp. 93-104, 1997.

Sefton, C.E.M. and Boorman, D.B., A Regional Investigation of Climate Impacts on UK Streamflows. *Journal of Hydrology* (in press), 1997.

Water Victoria: A Resource Handbook, Department of Water Resources, Melbourne,Australia, 311 pp, 1989.

Ye, W., Jakeman, A.J. and Barnes, C., A Parametrically Efficient Model for Prediction of Streamflow in an Australian Benchmark Catchment with Complex Storage Dynamics. *Environment International*, 21(5), pp. 539-544, 1995.

Young, P.C., The Instrumental Variable method: A Practical Approach to Identification and Parameter Estimation, in H.A. Barker and P.C. Young (eds.), *Identification and System Parameter Estimation*, Oxford, Pergamon, pp 1-16, 1985.

Young, P.C., Parallel Processes in Hydrology and Water Quality, *Jnl. Inst. Water Eng. And Management*, 5, pp. 598-612, 1992.

Young P.C., Schreider S.Yu. and Jakeman A.J., A Streamflow Forecasting Algorithm and Results for the Upper Murray Basin, MODSIM97, *Proceedings International Congress on Modelling and Simulation*, A.D. McDonald *et al.* (eds.), University of Tasmania, Hobart, December 8-11, 1997.