Land Use Effects on Potential Streamflow Response: the Murray-Darling Basin, Australia

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Abstract Anecdotal evidence suggests that farm dams have an impact on the streamflow regime, particularly at low flows. There is however a notable absence of suitable information on the nature and magnitude of these impacts. This work seeks to address this knowledge gap by identifying the nature of the impact of farm dams on catchment hydrology in the Murray-Darling Drainage Division. The eleven catchments selected for this analysis span zones of the Division with very different climatic and land use conditions. The extensive increase in farm dam development over the last two decades is considered to be an important land use factor affecting the streamflow regime in the catchments considered. Statistically significant reductions in potential streamflow response (PSR) were consistently detected for two catchments, the Yass River and Broadwater Creek. Average annual linear reductions in PSR were 8% and 9% of mean annual flow in the two catchments respectively, compared to average annual linear increases in catchment farm dam volume of 1.5% and 3.3% of mean annual flow respectively. In other words, a 1 ML increase in farm dam storage corresponded to a 5.5 ML decrease in catchment yield in the Yass River catchment, whilst a 1 ML increase in storage in the Broadwater Creek catchment corresponded to a 2.8 ML decrease in catchment yield. The remaining nine catchments displayed no statistically significant reductions in PSR. Farm dam volume information was available for four of these catchments, which displayed significantly smaller increases in farm dam volumes (not more than 0.3% of mean annual flow per year) compared to the Yass River and Broadwater Creek catchments.

1. INTRODUCTION

1.1 Potential streamflow response

The core problem of the definition of the term 'streamflow response' is that streamflow responds to a number of different factors. These factors can be roughly subdivided into 'climatic' and 'non climatic' ones. Each of these categories also comprise many affecting factors. For instance, the climatic influence on flow is a combination of temperature, precipitation, evaporation, wind speed and direction, level of cloudiness etc. Even a basic climatic factor, such as precipitation or temperature, can influence runoff differently depending on the intradiem distribution of these characteristics. Non climatic factors affecting streamflow include catchment vegetation and canopy changes and changes in human-induced water diversion and detention (dam construction, irrigation, urban water use etc.). Among the climatic factors impacting on streamflow response only precipitation and temperature are examined in the present paper.

Naturally, the streamflow regime is also affected by some 'constant' characteristics of the catchment, such as catchment terrain structure and soil types. The different responses to such characteristics are not considered here. Rather it is the response for a particular catchment to changing conditions that is addressed. The adjective '*potential*' should be added before the phrase 'streamflow response' when hypothetical streamflow behaviour is examined under different land use and vegetation scenarios. Thus, the final definition of the term 'potential streamflow response (PSR)' as it is used in this work could be stated as follows:

PSR is a catchment property reflecting the ability of streamflow to react to given temperature and

precipitation time series under different land use and vegetation conditions.

1.2 Methodology

It should be emphasised that PSR is a qualitative characteristic of a catchment. The primary aim of this work is to construct a quantitative function reflecting the catchment PSR and to develop a methodology allowing one to compute its temporal changes (ΔPSR) from observed streamflow.

The methodology employed in this work for estimating ΔPSR of selected catchments is based on the application of a conceptual rainfall-runoff model IHACRES (Jakeman *et al.*, 1990; Evans and Jakeman, 1997). This model is based on the Unit Hydrograph technique and allows one to filter the major climatic factors (precipitation and temperature) affecting catchment PSR. The IHACRES model was selected as a modelling tool because it has been successfully tested for streamflow modelling in Australian catchments and worldwide (e.g. Jakeman and Hornberger, 1993; Schreider *et al.*, 1996; Ye *et al.*, 1997), in a range of catchment hydroclimatologies, including those producing ephemeral, low-yielding streamflows. The model is calibrated for a selected time period, one-three years for catchments in this study, then a simulation run is implemented for the whole period for which the observed streamflow data are available. The parameters of the IHACRES model are designed to reflect the landscape and land use characteristics for the period of calibration of the catchment considered. Therefore, if the model is calibrated under different land use conditions, the historic streamflow response of the catchment, mirrored in measured flow, and any model simulation of streamflow, reflecting the PSR under the land use and vegetation conditions during the calibration period, must be different. Application of the IHACRES model allows one to quantify the PSR (simulated daily flow) and ΔPSR (residuals of simulated flow defined as differences between daily measured and modelled values) under given climatic conditions. A reduction in the ΔPSR over time is reflected in the underestimation by simulated values of observed streamflow for periods before the calibration period and in the overestimation for periods after calibration.

The overall approach adopted for the analysis was to:

1. Investigate land use changes in each catchment and where possible, quantify the changes in farm dam volume over the period of streamflow record.
2. Calibrate the conceptual rainfall-runoff model IHACRES to a series of short (1 to 3 years) periods.
3. Generate a time series of streamflows using IHACRES. As the parameters of the IHACRES model are defined largely by landscape and land use characteristics (not climate), simulation runs with a calibrated model reflect the nature of these characteristics in the catchment over the calibration period.
4. Calculate streamflow residuals (observed flows minus simulated flows) over the period of record. The differences between observed and simulated discharge predominantly reflect the effect of changes in non-climatic conditions over the period of simulation.
5. Perform trend analyses on these streamflow residuals to determine whether there has been a reduction in potential streamflow response. Two different methods of trend analysis, Estimated Generalised Least Square (EGLS) and Generalised Additive Model (GAM), were employed in the present work.
6. Correlate these changes in potential streamflow response to changes in land use.

A number of shortcomings with the above approach were however identified. In particular, the identification of trends is heavily dependent upon the quality of the IHACRES model calibration, as there is a trade-off between requiring a long period of calibration to minimise bias in the calibration, and needing a short period of calibration to ensure stationarity with respect to farm dam development. In addition, reductions in potential streamflow response due to farm dam development were not distinguishable from the impacts due to other land use changes.

1.3 Catchments selected for the analysis

The emphasis in this study is on the influence of an increase in farm dams on the PSR. Thus the major basis for selection of catchments for analysis is an increase in the number of farm dams in the study area.

Additional selection criteria of catchments was based on minimum data requirements including:

- 10 years of streamflow, rainfall and temperature records
- Reasonable quality of stream gauging according to AWRC rating.

Approximately 40 potential catchments that satisfy these criteria were selected across the Murray Darling Drainage Division. Liaison with local State agency officers in these catchments provided essential background information on land use development, key issues and concerns. In addition, preliminary arrangements were made concerning the availability of aerial photographs for loan during the study. As a result, a short list of eleven key catchments was selected. Table 1 gives a short list of catchments where the IHACRES model was successfully calibrated and trend analysis for the model residuals was undertaken. The distribution of these catchments within the Murray-Darling Drainage Division is shown in Figure 1.

Figure 1 Map of the Murray-Darling Drainage Division and its Basins

Table 1 Short list of catchments selected for the analysis

Catchment	Area (km^2)	Basin
Morses Ck	128	Ovens
Hurdle Ck	155	Ovens
Peel R	407	Namoi
Warrah Ck	150	Namoi
Duncans Ck	93	Namoi
Swamp Oak Ck	391	Namoi
Yass R	388	Murrumbidgee
Campbell R	950	Macquarie
Green Valley Ck	119	Macquarie
Pyramul Ck	193	Macquarie
Broadwater Ck	108	Border

2. SUMMARY OF THE IHACRES MODELLING

The conceptual rainfall-runoff model IHACRES was successfully calibrated for all 11 catchments selected for the analysis. The models were identified for 1 – 4 calibration periods (CPs) with duration of 1 – 3 years in each catchment considered. The calibration results were evaluated using the Nash-Sutcliffe efficiency (R^2) and bias. The description of the calibration procedure, definitions of the model parameters and the basic model convergence statistics can be found in Schreider *et al.* (1996) and Evans and Jakeman (1997). The results of calibration for all 11 catchments considered are summarised in Table 2.

Table 2 Results of the IHACRES calibrations

Catchment	Number of CPs	Efficiencies (R^2)
Morses Ck	3	0.71 – 0.87
Hurdle Ck	4	0.80 – 0.93
Peel R	4	0.65 – 0.86
Warrah Ck	1	0.89
Duncans Ck	4	0.73 – 0.86
Swamp Oak Ck	3	0.67 – 0.80
Yass R	2	0.83, 0.97
Campbell R	4	0.79 – 0.90
Green Valley Ck	1	0.85
Pyramul Ck	2	0.74, 0.76
Broadwater Ck	2	0.91, 0.92

Figure 2 illustrates the model performance for the Morses Creek catchment.

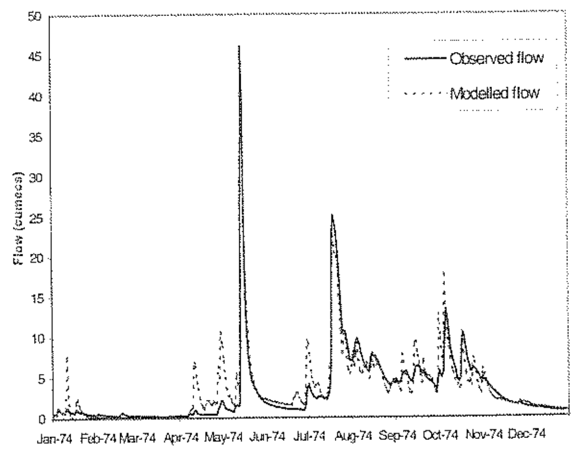

Figure 2 Illustration of the model calibration performance for the Morses Creek catchment

3. STREAMFLOW TREND ANALYSIS

3.1 Methods

The aim of this part of the study was to identify changes in streamflow response over periods of farm dam development. The general method adopted to assess trends in streamflows was to:

1. Generate a time series of streamflows over the period of analysis using the calibrated IHACRES rainfall-runoff models.
2. Calculate streamflow residuals (i.e. the change in potential streamflow response, ΔPSR) between observed and estimated streamflows.
3. Perform a trend analysis on these residual values.

Streamflow trends were characterised in two ways, namely by undertaking:

- trend analyses of smoothed residuals using the EGLS method; and
- formal parametric trend tests using the GAM.

Each of these methods is described below.

3.2 Estimated Generalised Least Squares method on smoothed residuals

The EGLS method was initially used to identify streamflow trends. The algorithm for identifying the trend in the ΔPSR is described as follows:

1. The model calibrated for each period is simulated over the entire period for which observed streamflow data are available.
2. The mean daily model residuals are calculated for some interval (2 year periods were arbitrarily selected). A step of *n* days between interval start dates is used (*n* = 50 here).
3. Graphs of these residual values (ΔPSR) are plotted against the starting date of each interval for the whole period considered.
4. A linear regression for the model residuals versus time is calculated for each model found for the catchment. As was described in Section 1.2, a negative trend in residuals is interpreted as a reduction of the ΔPSR, and a positive trend as an increase.

The residual time series were found to be autocorrelated, that is, errors of the linear model describing the trend in the residual time series were dependent on previous error values. Ordinary least squares (OLS) regression is based on the assumption that the errors are independent and identically distributed. Thus OLS was not an appropriate technique for estimating trend values in these data series as OLS estimates under these conditions are asymptotically consistent but inefficient, making estimates of the significance of trend curves relatively meaningless. Therefore, to allow for the construction of approximate significance tests on the resulting trend estimates, the estimated generalised least squares (EGLS) method was employed. A complete description of the EGLS method can be found in Judge *et al.* (1980).

3.3 Generalised Additive Model (GAM) trend analysis

The GAM models applied in the present work were of the following general form:

Model residual = constant + f(time) + f(season) + f(rainfall) + f(autocorrelation(ε)),

where f(variable) denotes a functional relationship between the model residual and the variable concerned. A spline with three degrees of freedom was applied to rainfall data, whilst a spline with two degrees of freedom was applied to the time variable.

The basic aim of including functional relationships as explanatory variables is to remove the influence of the selected variable. It is seen that in essence the approach is similar to that used in multiple regression, though with the GAM approach the functional relationships are treated as independent variates in order to remove, with as little bias as possible, the influence of the selected variable. It is important to note that all functional relationships are fitted jointly. A more detailed description of the GAM approach and examples of its application to a range of practical problems can be found in Hastie and Tibshirani (1990).

Trend analyses were completed on a monthly, quarterly and half-yearly time step, using both linear and spline functions for the time trend. Seasonality was only fitted to monthly data. Rainfall was fitted with a spline function to help remove any residual model bias from the IHACRES calibration. Values of linear trend (Table 3) were reported for the analysis performed on a quarterly time step.

3.4 Inventory of results

The results of the trend analyses varied for the individual catchments considered. The key results for these catchments are as follows:

1. Reductions in PSR were consistently detected for 50% or more of model runs in the following two catchments:

- Yass River at Gundaroo; and
- Broadwater Creek.

Table 3 presents the trend analysis results for these two catchments. Figures 3 and 4 illustrate the EGLS and GAM trends in these catchments.

Table 3 The ΔPSR trend analysis results for the Yass and Broadwater catchments

Catchment	ΔPSR Time Trend (ML/yr)	Farm Dams Trend (ML/yr)	Significance of Time Trend
Yass R.	-1700	300	5%
Broadwater Ck	-550	200	5%

The magnitude of these reductions was significantly greater than the increase in farm dam volume in the catchment over the period of analysis. This indicates that the impact of farm dams on streamflow may be greater than the volumes of the farm dams themselves. Plausible explanations for this effect include an enhanced evaporation from the dam surfaces during the summer period, and the additional impacts of land use changes associated with farm dam development.

2. No statistically significant trends were detected in 50% or more of model runs in the following 8 catchments:

- Morses Creek at Wandiligong;
- Hurdle Creek at Bobinawarrah;
- Campbell River at Ben Chifley Storage;
- Pyramul Creek at u/s Hill End Road;
- Green Valley Creek at Hill End;
- Peel River at Chaffey Storage;
- Warrah Creek at Old Warrah; and
- Swamp Oak Creek at Limbri.

3. A statistically significant increase in PSR was detected in 50% or more of model runs in the Duncans Creek catchment.

4. When the flow records for the Green Valley Creek and the Campbell River (Ben Chifley) catchments were divided into segments pre- and post-1984, statistically significant decreases in PSR were detected prior to 1984, whilst no trends or significant increases in PSR were detected after 1984. The detailed analysis of PSR trends in the Macquarie Basin can be found in the companion paper Letcher *et al.* (1999).

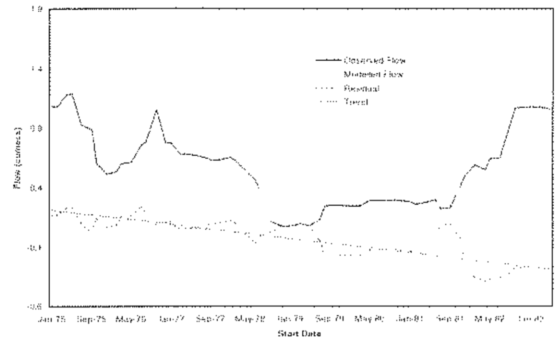

Figure 3 The EGLS residual trend analysis for the Yass River catchment

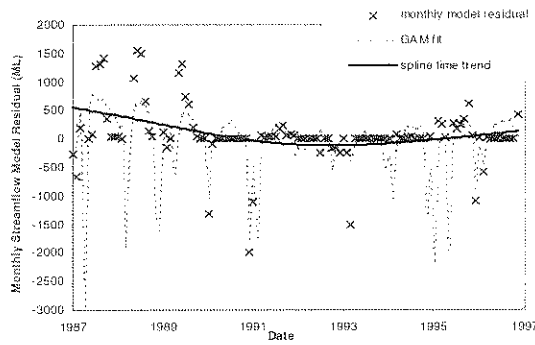

Figure 4 GAM trend for the Broadwater Creek catchment

5. When low flows for the four catchments in the Namoi Basin were analysed, a weak decrease in PSR was detected in the Swamp Oak Creek catchment, whilst no trends were detected in the Peel River (Chaffey Dam), Warrah Creek or Duncans Creek catchments.

4. DISCUSSION AND CONCLUSIONS

Results and conclusions for this work include the following:

1. The hybrid metric/conceptual rainfall-runoff model IHACRES was successfully calibrated for 11 catchments in the Murray-Darling Drainage Division belonging to regions subject to a range of climatic and land use conditions.

2. A methodology allowing one to indicate the non-climatically driven changes in the potential streamflow response to different land use conditions was developed. This methodology is based on a trend analysis of the IHACRES model residuals calculated as the change in potential streamflow response (ΔPSR): the difference between streamflow over the entire instrumented period in the catchments and the potential streamflow under the land use conditions in the period over which the model is calibrated. Two methods of trend analysis were tested in this study. These are the EGLS and GAM algorithms. Similar results for the trend analysis were obtained using both algorithms.

3. Significant changes in the PSR caused by non-climatic changes in catchment conditions were found for a majority of calibration runs in the Yass River and Broadwater Creek catchments in the Murray-Darling Drainage Division. The total volume of the farm dams in these catchments as a percent of their mean annual flow is largest among the six catchments for which information on farm dam volume was available (see Table 4). **From this it can be concluded that the catchments with the two largest increases in farm dam volume (at least 1.5% of Average Annual Discharge) clearly displayed statistically significant reductions in PSR.**

Table 4 Trend analysis results in relation to changes in farm dam volumes

Catchment	Average annual increase in farm dam volume (ML/yr)	Average annual increase in farm dam volume as % of mean annual flow
Peel R	150	0.3 %
Duncans Ck	5	0.04 %
Swamp Oak Ck	42	0.1 %
Warrah Ck	14	0.2 %
Yass R	300	1.5 %
Broadwater Ck	200	3.3 %

4. The magnitude of the reduction in ΔPSR in the Yass and Broadwater catchments are considerably larger than the average annual increase in farm dam capacity over the same period (cf. Table 3). **From this it can be concluded that streamflow in catchments under intensive farm dam development is affected not only by direct detention of water in these dams, but also by associated land use changes and other losses such as evaporation, seepage and water use for agricultural purposes.**

5. The trend analysis results for the Ben Chifley catchment of the Macquarie Basin showed a negative trend in ΔPSR before 1984 and a positive trend after this year. This statistically significant trend result was found using the EGLS algorithm. Similar tendencies in changes in PSR, but with lower statistical significance, were found for other catchments of this Basin (see also Letcher *et al.*, 1999).

Future study assessing trends in streamflows due to human induced impacts should be primarily oriented to the development of methods to separate the impacts of different land/water use scenarios on streamflow response. Especially important is the collection of **quantitative** information about changes in the total capacity of the farm dams and other water diversions in the catchment under consideration.

5. References

Evans, J.P. and Jakeman, A.J. Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. *MODSIM97*, Vol. 1, 222-227, 1997.

Hastie, T.J. and Tibshirani, R.J. Generalised additive models. Chapman and Hall, London. 1990.

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

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

Judge, G.G., Griffiths, W.E., Hill, R.C. and Lee, T.C., The theory and practice of econometrics, John Wiley and Sons, USA, 1980.

Letcher, R.A., Schreider, S.Yu., Neal, B.P., Jakeman, A.J. and Nathan, R. J. Comparison of methods for potential streamflow response analysis in the Macquarie River Basin, *MODSIM99*, this volume.

Schreider, S.Yu., Jakeman, A.J., and 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*, 36, 513-546, 1996.

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