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Towards model adequacy for identifying the impacts of climate and land use on catchment hydrology

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Abstract: Land use and climate change/variability can have a major impact on catchment hydrology and these impacts can be strongly interrelated. This paper is part of a study that has an ultimate objective to isolate the impacts of land use change on streamflow from those of climate variation in the upper Murrumbidgee catchment, south-eastern Australia. The aim is to investigate the consistency or variability of catchment response and model parameters and performance over time and space. Subcatchments located in the upper part of the Queanbeyan (at Tinderry), Cotter (Gingera), Goodradigbee (Brindabella), Molonglo (Burbong) and Orroral (Crossing) Rivers with daily rainfall-discharge data for 40 years or more and minimal impact from dams have been selected for the study. As often occurs in non-experimental catchments, the land use in these catchments is closely correlated with climate differences, making a classic paired catchment study impossible. Instead, future research will focus on determining under what conditions the model performs well, and investigating whether a land use signal can be detected in the resulting subset of the data.

For this purpose, both data- and model-based analyses of the dynamic relation between rainfall and runoff for these subcatchments are presented. Prior to performing the analyses, the rainfall data from selected stations have been checked and corrected to reduce the impact of errors in the areal rainfall estimates. Data analysis techniques (e.g. trend analysis, deconvolution and baseflow filtering) are used to assess the temporal and spatial variation in the hydrologic response characteristics for each site. The lumped conceptual rainfall-runoff model IHACRES CMD (Catchment Moisture Deficit) version is applied to the subcatchments to assess the adequacy of the model response in representing the impact of weather patterns on streamflow. A number of performance criteria have been used to evaluate the performance of the model in each calibration period using a multi-criteria approach.

Data-based analysis shows that there has been a significantly stronger decline in streamflow compared to rainfall in all subcatchments after 1990. This decreasing trend in streamflow was more prominent at Burbong and Tinderry, with these subcatchments having lower and more variable storage capacity (the combined surface and sub-surface storage capacity of the catchment inferred from the data-base analysis) than the other subcatchments. The model-based analysis revealed that Tinderry required at least a 6 year length of record to stabilize performance statistics and yield parameter consistency in calibration. Subsequently, an 8 year calibration period was used for all subcatchments. Gingera and Brindabella showed good model performance for all performance indicators, while Tinderry, Burbong and Orroral Crossing showed poor to average model performance in R^2, R^2_{ln} and bias. The reduction in performance in R^2 for Tinderry and Burbong subcatchments was due to the poor fitting to the peaks for both large and small streamflow events, with the model underestimating the highest flow peaks, and overestimating smaller peaks. This suggests that the effective rainfall and/or the quick flow volume for large events are underestimated in the IHACRES model for these catchments.

Further work will be needed to improve model performance for Tinderry and Burbong subcatchments in order to separate the impacts of climate variations and land use change on hydrological response. An appropriate model structure having a variable partitioning between quick and slow flow components is under consideration. Different drivers of the variability in the partitioning are being explored, including relating the slow flow volume to effective rainfall depth, seasons and rainfall depth. In addition, modifications to the CMD module of IHACRES are being investigated to improve the estimation of the effective rainfall for large streamflow events.

Keywords: *Land use change, climate change, climate variability, data-based analysis, model-based analysis, model adequacy*

1. INTRODUCTION

With climate change and water use competition being ever more important considerations in catchment management, improved understanding of the sensitivity of catchment response to climate and land use changes is paramount. This includes understanding the susceptibility of a catchment's response characteristics to shifts in the magnitude, intensity and seasonality of rainfall, length of dry spells and temperature increases, as well as the impact of large-scale land use change.

The effects of land use change on streamflow are easily veiled by climate variability because the impacts of land use change can be comparatively small compared to those of climate variations. Additional factors impeding the separation of land use change impacts from the effects of climate variability on streamflow are: lack of good quality streamflow records prior to the development period of interest; lack of relevant land and water use data, such as the changing density and volumes of farm dams and groundwater extractions over time; and uncertainty of simulation models that capture such effects (Letcher et al., 2001; Neal et al., 2002; Schreider et al., 2002). Impacts of land use change can also be hidden by errors in areal rainfall estimates, when those errors are larger than the effects of land use change on streamflow.

In recent years, a wide range of rainfall-runoff models has been used to assess impacts of climate and land use change on the hydrological cycle. Lørup et al. (1998) and Letcher et al. (2001) used lumped conceptual hydrological models for predicting the effects of land use change on streamflow. They assessed long-term impacts of land use change and distinguished the effects of climate variability and land use change on semi-arid catchments, using statistical analysis and hydrological modelling, and assuming that their models could account for the influence of climate variability. However, identification of statistical significance and trends in model residuals heavily depends on the quality of the rainfall-runoff model calibration. Viney et al. (2005) used ensemble modelling to reduce uncertainty in the predictions of the hydrological impacts of land use change. Ten models were applied to a river basin in central Germany using three land use change scenarios. The study demonstrated the potential of an ensemble approach to provide more accurate hydrological predictions than those based on individual models.

Paired catchment studies are widely used to investigate the hydrological response of a catchment to land use change. This approach can significantly reduce the impact of climate variability on hydrological response through the comparison of two catchments subject to the same climatic conditions under different land uses, and thus provide a useful method for separating land use impacts from climatic factors in relatively small catchments (Brown et al., 2005). Catchment characteristics like slope, aspect, soils, area, climate and land use need to be comprehensively identified in cases where the paired catchment approach is considered in medium-sized catchments (100~2,500 km^2) (Lørup et al., 1998). Brown et al. (2005) reviewed various kinds of paired catchment studies for determining the changes in water yield at many different time scales caused by afforestation, deforestation, regrowth and forest conversion. They compared the changes in mean annual yield documented in previous paired catchment reviews with a mean annual water balance model. This analysis indicated good agreement between the paired catchment and the mean annual water balance approach. Wang et al. (2008) used SWAT (Soil and Water Assessment Tool) to investigate the impacts of different land use and climate change scenarios on monthly flows for a mountainous catchment in the arid region of northwest China. Model outputs indicated higher variance in flows with climate change than land use change, which suggests that changes in flows caused by land use change would be more difficult to predict under high climate variation scenarios (Schade and Shuster, 2005). Changnon and Demissie (1996) were able to identify relationships between streamflow and precipitation to measure the effects of climate and land use changes on annual mean and peak streamflow in paired rural and urbanized catchments.

This study focuses on initial steps in an ultimate objective of isolating the impacts of land use change on streamflow from those due to climate variation. This involved both data and model-based analyses of the dynamic relation between rainfall and runoff, enhanced by comparative analyses among different subcatchments. Rainfall data from selected stations have been checked and corrected for identifiable errors to reduce data uncertainty. Data analysis techniques (e.g. trend analysis, deconvolution and baseflow filtering) were used to develop appreciation of the temporal and spatial variation in the hydrologic response characteristics for each site. The lumped conceptual rainfall-runoff model IHACRES CMD (Catchment Moisture Deficit, Croke and Jakeman, 2004) version was applied to the subcatchments to evaluate the predictive error and consistency of catchment response. The model performance was assessed for each catchment, with a view to identifying shortcomings in the model and investigating methods of improving the model structure to reduce these deficiencies.

2. STUDY SITE

The upper Murrumbidgee Catchment located in the Southern Tablelands of south-eastern Australia covers an area of 13,090 km^2 and is part of the headwaters of the Murray-Darling Basin. The catchment is highly valued for its unique environments, fisheries, forests and other natural resources. The climate varies both temporally and spatially within the upper Murrumbidgee Catchment. Summers are dry (where evaporation may be greater than precipitation) and winters are cold with low evapotranspiration rates (Carter et al., 1994). Average annual rainfall across most of the catchment is in the 500 to 900 mm range, with a high rainfall variation through the year (Murrumbidgee Catchment Management Committee, 1998). The main land uses are urban, rural residential, grazing (improved and native pastures), cropping, horticulture and orchards, forestry (softwood plantations) and native timber (Carter et al., 1994).

The subcatchments studied in this paper are located in the upper part of the Queanbeyan, Cotter, Orroral, Goodradigbee, and Molonglo River catchments, and were selected based on rainfall gauge density and consistency of rainfall and streamflow data quality, and avoiding those with significant regulation due to large dams. The subcatchments for Queanbeyan River at Tinderry (410734) and Molonglo River at Burbong (410705) are affected by considerable surface water (farm dams) and groundwater development, while Cotter River at Gingera (410730), Goodradigbee River at Brindabella (410088) and Orroral River at Crossing (410736) are less developed catchments. Information on the stream gauges for the subcatchments is listed in Table 1. The location of the subcatchments and stream gauge stations, and the mean annual rainfall surface are shown in Figure 1.

Table 1. Stream gauging station information for the subcatchments analyzed.

Station ID	Area (km^2)	Elev. (m)	Period	Missing (%)
410088	427*	1,197*	02/08/1959 17/01/2006	4.8
410705	505*	682*	16/03/1929 08/03/2006	1.0
410730	148*	958*	03/01/1964 12/06/2003	0.2
410734	506**	785*	04/08/1966 08/05/2006	0.4
410736	90*	870*	01/10/1967 16/02/2006	1.8

** Source: AGRICON (2005)
* Source: Bureau of Meteorology: http://www.bom.gov.au/hydro/wrsc

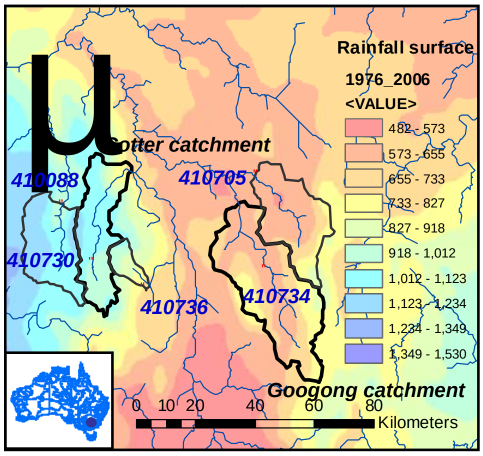

Figure 1. A map of the subcatchments in the upper Murrumbidgee Catchment with mean annual rainfall surface and stream gauging stations selected for analysis.

3. METHOD

The overall method is a combined approach, incorporating both data- and model-based analyses. This combined method will complement the weaknesses of each approach to detect the temporal and spatial variation in streamflow and infer catchment response characteristics.

3.1. Data-based analysis

Kim et al. (2007) applied data-based analysis techniques (trend analysis, deconvolution and baseflow filtering) to the Tinderry and Gingera catchments. Details of the techniques are given in Kim et al. (2007) and references therein. To extend this work, similar analysis of the data for Brindabella, Burbong and Orroral Crossing gauges has been carried out, with Burbong showing similar response characteristics to Tinderry, while Brindabella and Orroral Crossing are closer to the response seen at Gingera. While the previous study focused on the temporal variation in the response, this work also includes an analysis of the variation in the total unit hydrograph (combined response due to all flow pathways, including baseflow) related to the magnitude of the event flow peak.

3.2. Model-based analysis

The lumped conceptual daily rainfall-runoff model IHACRES was used for the model-based analysis component. The IHACRES model includes a non-linear loss module (the Catchment Moisture Deficit (CMD) version of Croke and Jakeman, 2004) to estimate the effective rainfall, and a linear routing module to model the conversion of the effective rainfall into streamflow. The length of record needed to obtain consistent parameter values and statistics in calibration was studied, with model calibrations performed using 3 to 10 year calibration periods spanning from 1968 to 2002 for the Queanbeyan River at Tinderry and Cotter River at Gingera. Multiple calibration periods were used in order to test for time-invariance in the parameter values. The model performance was assessed using NSE (Nash-Sutcliffe Efficiency), NSE incorporating a log transformation of daily flows, bias, correlation coefficients and RMSE (Root Mean Square Error) of the flow duration curve. And 'best' model fits in each calibration period were selected by considering trade-offs among multiple statistics.

4. RESULTS

4.1. Data-based analysis

A 10 year moving average of streamflow and rainfall data shows a strong decline in streamflow after 1990 in all subcatchments, while decreases in rainfall are not as noticeable. This decreasing trend in streamflow is more prominent for Burbong and Tinderry (subcatchments with the lowest rainfall) than in the other subcatchments. Using a baseflow filtering approach (Croke et al., 2001), there is no significant trend in annual baseflow fraction for any of the study sites over the available data period. Burbong has comparatively small and variable annual baseflows (similar to Tinderry, Kim et al. 2007). Baseflow filtering shows that Brindabella and Orroral Crossing have a dominant baseflow response (similar to Gingera), while the quick flow response is much stronger in Burbong and Tinderry.

Figure 2 shows non-parametric impulse response estimates based on an average event unit hydrograph (Croke, 2006) for large (high flow), small (low flow), and all streamflow events at Tinderry and Gingera. High flows are defined as having event peaks greater than 1,300 ML/day at Tinderry and 800 ML/day at Gingera. Low flows consist of small events having peaks less than these threshold values for each subcatchment. In general, the hydrograph has steeper recession curves for large streamflow events (high flows in Figure 2) than for small events (low flows). In the log-log plot, the difference between large and small event response for time since peak at Tinderry compared with Gingera can be seen more clearly. Burbong shows a similar shape of impulse response estimates to Tinderry, and Brindabella and Orroral Crossing have similar responses to those seen in Gingera. They indicate that event size affects the calibration of linear parameter values in the routing module for Tinderry more than for Gingera.

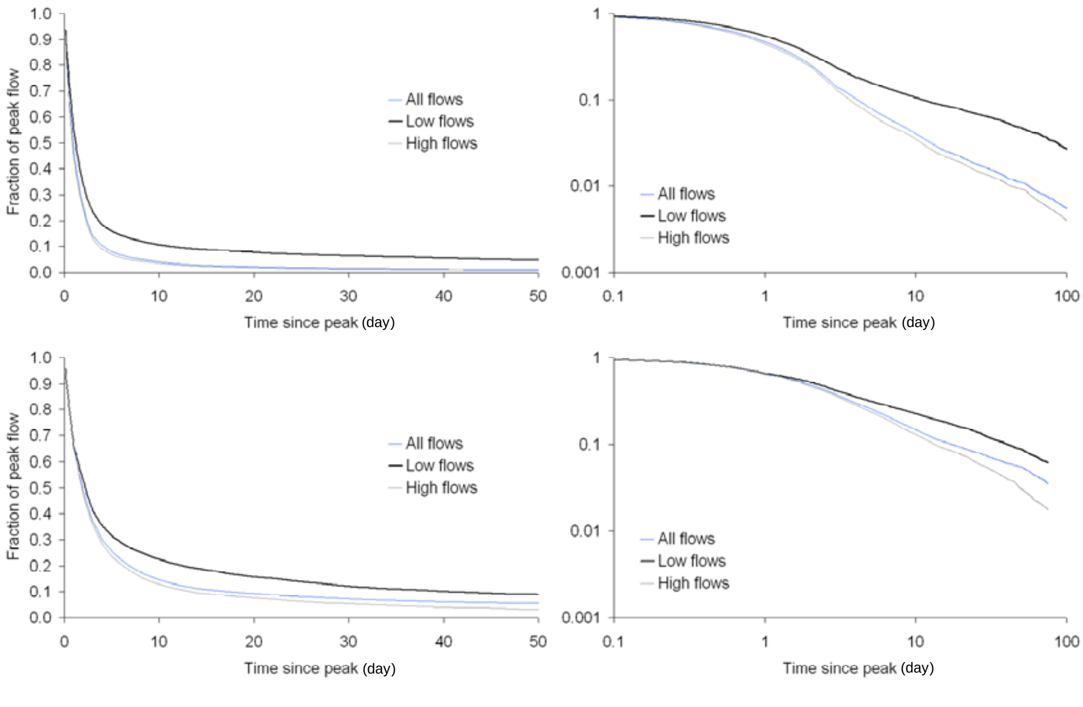

Figure 2. Non-parametric impulse response estimates for Tinderry (top panel) and Gingera (bottom); linear (left) log-log (right) scale

4.2. Model-based analysis

The convergence of the IHACRES model parameters to time-invariant values with increasing length of calibration period was checked using mean and average CVs (Coefficients of Variation) of: model performance indicators (NSE (R^2), NSE incorporating a log transformation of flows (R^2_{ln}), bias, correlation coefficients, and RMSE of the flow duration curve); and of parameters (volume of slow flow - v_s, slow flow recession time constant - τ_s, quick flow recession time constant - τ_q, drainage equation shape parameter - b, and stress threshold - f). These were plotted against the length of the calibration period. The values of R^2 and R^2_{ln} at Gingera, and R^2 at Tinderry are time-invariant across the range of calibration period tested, while R^2_{ln} for Tinderry is significantly improving as calibration period increases up to 6 years in length, and stabilizes from the 8 year calibration period (see Figure 3 top panel). CVs of parameter values are stable through increasing length of calibration period at Gingera. In contrast to Gingera, v_s and v_q are variable at the 3 and 4 year calibration period, and stabilize from the 8 year calibration period at Tinderry (see Figure 3 bottom panel). Therefore, at least 6 years or more length of record is needed to stabilize statistics and detect parameter consistency in calibration for catchments with similar response characteristics to Tinderry. In this study, an 8 year calibration period is selected, based on the evaluation of catchment response characteristics over different period lengths at Tinderry.

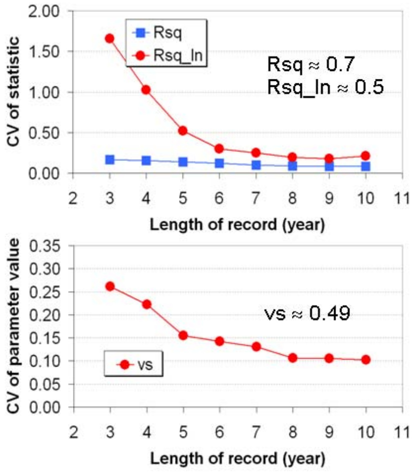

Figure 3. Average CV of statistics (top panel) and slow flow parameter values (bottom) for 3 to 10 year calibration periods at Tinderry.

Based on the 8 year calibration period, there was good model performance (over 0.7 in R^2 and R^2_{ln}) and strong temporal stability (see Figure 4) in statistics at Gingera and Brindabella, while poor model performance (less than 0.7 in R^2 and 0.5 in R^2_{ln}) and large temporal variation (see Figure 4) in statistics are evident at Tinderry and Burbong. Tinderry and Burbong show greater sensitivity to model performance in R^2_{ln} than Gingera and Brindabella. In general, the bias is small and stable throughout the available data period at Gingera and Brindabella; but shows large variation at Tinderry and Burbong. In comparison, the slow flow volume shows a slight increasing trend at Gingera and Brindabella, though this is not substantial. The sample plots for model performance and parameter consistency at Tinderry and Gingera are shown in Figure 4.

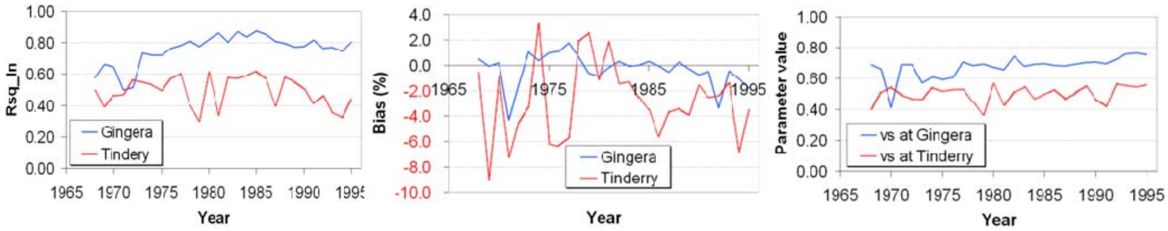

Figure 4. Statistics (left and middle) and slow flow volume (right) over the 8 year calibration period at Gingera and Tinderry (year indicated on x-axis is the start of the 8 year calibration period).

The behaviour of the model in representing flow for large and small events for Tinderry and Gingera is shown in Figure 5. The model systematically underestimates high flows and partially overestimates low flows. Underestimation in high flows is more predominant at Tinderry.

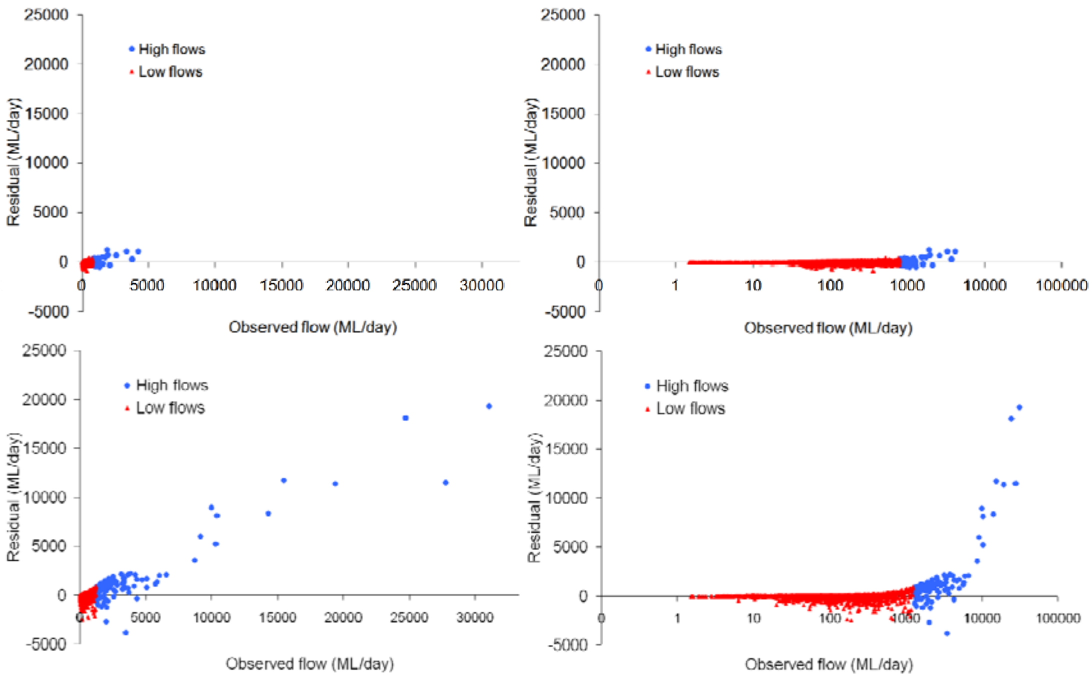

Figure 5. Scatter plots of residual and observed flow for Gingera (top panel) and Tinderry (bottom); linear (left) log-linear (right) scale

5. DISCUSSION AND CONCLUSIONS

Model performance is still inadequate, particularly for the eastern catchments (Tinderry and Burbong), due at least partially to non-stationarity in the total unit hydrograph (more significant in the eastern catchments). Other causes for the poor model performance are being investigated (e.g. impact of losses from the groundwater systems), though to date, this is still work in progress. As a result, it is still difficult to discern the impacts of land use on streamflow response in the study sites. While the ideal situation would be to have data for undeveloped catchments with similar climate to Tinderry and Burbong, such data are not available. Instead, the focus of future research will shift to investigating under what conditions the model performs reasonably well and determine if land use impacts can be seen for this subset of the data.

Data- and model-analysis techniques have been used to examine the changes in the relationship between rainfall and runoff in selected subcatchments in the upper Murrumbidgee catchment. Burbong subcatchment shows similar dynamics in hydrological response to Tinderry, while Brindabella and Orroral Crossing have similar responses to those seen in Gingera. Burbong and Tinderry have lower and more variable storage capacity (the combined surface and sub-surface storage capacity of the catchment) than the other subcatchments and are subject to a different rainfall regime with a higher proportion of rain in the warmer months. In the model-based analysis, Tinderry and Burbong required at least a 6 year length of record to stabilize performance statistics and yield consistent parameter values in calibration. Gingera and Brindabella showed good model performance and strong temporal stability in model performance, and this suggests that the model is adequately (though not perfectly) representing the impact of climate variability on the response of these catchments. On the other hand Tinderry, Burbong and Orroral Crossing showed poorer model performance and significant temporal variation in R^2_{ln} and bias.

In general, long term water balance models have difficulties in calibrating both high and low flows well. Investigation of the model performance in terms of peak height of events shows that the model is not fitting the variability in the event peak flows observed at Tinderry and Gingera, with the error more significant for Tinderry. Poor model performance is strongly related to the large difference in impulse response estimates for low and high flow. Underestimation of high flows and overestimation of low flows suggest that the effective rainfall and the quick flow volume for large events are underestimated in the IHACRES model.

Further work will be needed to improve model performance for some catchments. Proposed changes to the model include modification of the CMD loss module to increase effective rainfall for large rainfall events. An appropriate model structure having a variable partitioning between quick and slow flow components is under consideration. Different drivers of the variability in the partitioning are being explored, including relating the slow flow volume to effective rainfall depth, seasons and rainfall depth.

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