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Towards better understanding of changes in rainfall-runoff relationships during the recent drought in south-eastern Australia

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It has been contended that during the 1997-2008 'Millennium' drought there was an unexpectedly large decline in runoff from some catchments in south-eastern Australia (SEA). Potter et al. (2011) suggested that across 34 unregulated catchments in SEA the area weighted reduction in streamflow during the drought was 46 percent. Sixty-five percent of this was attributed to reduction in annual rainfall and 7 percent to the direct or indirect effect of changes in average annual maximum temperature. The remaining 28 percent was unexplained residual; potentially due to changes in seasonality and inter-annual variability of rainfall; and/or anthropogenic change (i.e. in particular farm dams), change in vegetation or a change in dominant hydrological behaviour. In this study we aim to develop a better understanding of why the reductions in runoff under the recent drought have been so large and why the unexpected residual as computed by Potter et al. varied spatially.

To accomplish this, 34 unimpaired catchments with long streamflow and climate records from New South Wales and Victoria were examined. For each catchment a range of hydro-metrological metrics was computed, including runoff, rainfall, runoff coefficient, daily percentiles of rainfall (P) and runoff (Q), slow-flow and quick-flow and non-linear hydrograph recession constants for each season and each year of observed records. Rainfall-runoff modelling was undertaken using the Sacramento model on 111 unimpaired catchments across SEA (calibrated between 1975 and 1996) and assessed model bias during the drought.

A consistent pattern that emerged was that in southern SEA the catchments with low-relief and moderate rainfall (i.e. 600 to 900 mm) consistently showed statistically significant reductions in runoff coefficient, daily runoff percentiles, slow-flow and hydrograph recession constants during the drought, while the higher relief, high rainfall (> 900 mm) catchments in southern SEA did not. Yet all catchments in southern SEA experienced a similar reduction in mean annual rainfall during the drought (~17 to 22 percent). Petrone et al. (2010) surmised that in south-west Western Australia, a new hydrological regime had developed in many catchments over the recent record and they attributed this to falling groundwater levels. We propose that in the low-relief, moderate rainfall catchments of southern SEA, relatively high groundwater levels may have amplified overland flow during pre-drought conditions by reducing the storage capacity of the unsaturated zone and by facilitating organised patterns of drainage and the connection of source areas of runoff as the soil wetted up during a rainfall event. Under a falling watertable, the storage capacity of the unsaturated zone increased, and hence saturation conditions were less likely to occur, and the connectivity of source areas was likely to be less organised.

In the high relief, high-rainfall catchments, falling groundwater levels would have resulted in a reduction of groundwater baseflow to streams, but we contend that due to the higher relief of these catchments, groundwater levels do not act as a major control over the formation of areas of saturation or the organisation of soil moisture during an event.

The high rainfall over the spring/summer of 2010-11 will allow us to test our hypothesis further. Future investigations will also focus on the role of farm dams in contributing to the unexpected decline in runoff during the drought. During drought conditions farm dams will intercept a greater proportion of flow than during wet conditions. Understanding how catchments behave in times of drought may provide insights into how best to adapt hydrological models to better simulate runoff under drier climates.

Keywords: *rainfall-runoff, Millennium drought, surface-groundwater connection, south-eastern Australia, hydrological persistence, non-linearity*

1. INTRODUCTION

It has been contended that during the 1997 to 2008 'Millennium' drought there was an unexpectedly large decline in runoff from some catchments in south-eastern Australia (SEA). Potter et al. (2011) suggested that across 34 unimpaired catchments the area weighted reduction in streamflow during the drought was 46 percent. Sixty-five percent of this was attributed to reduction in annual rainfall and 7 percent to the direct or indirect effect of changes in average annual maximum temperature. The remaining 28 percent was unexplained residual; potentially due to changes in seasonality and inter-annual variability of rainfall; and/or anthropogenic change (i.e. in particular farm dams), change in vegetation or a change in dominant hydrological behaviour. The unexpected residual varied spatially.

Petrone et al. (2010) surmised that in south-west Western Australia, a new hydrological regime had developed in many catchments over the recent record. These authors undertook a trend and change point analysis of streamflow data. Trend tests showed a significant decline in annual rainfall and streamflow between 1950 and 2008, with corresponding change points for both rainfall and streamflow in the late 1960s or mid-1970s. Over the more recent record (1989 to 2008) however, streamflow decline in the south-west was observed as a step change although rainfall did not show a significant downward trend. The decline in streamflow over the recent record was attributed to falling groundwater levels.

In this study we investigate whether: i) there has been a change in hydrological behaviour of catchments in SEA; and ii) a 'falling groundwater' phenomenon could have contributed to the decline in runoff. Due to the complex nature of trying to demonstrate a change in hydrological behaviour during the drought we adopted a weight of evidence approach, where we tested multiple lines of evidence, using analytical and modelling techniques to infer whether there has been a change in hydrological behaviour.

1.1. Study area and station selection

For the purposes of the empirical analysis in this study, we required long, mostly complete, time series of observed streamflow data. From the gauging stations available in the SEA region, we chose a threshold of greater than 40 years of complete data, and less than 30 days of missing data in total between 1997 and 2008. Missing data were infilled using the Sacramento (Burnash et al. 1973) rainfall-runoff models. In order to rule out any effects from farm dams or land-use changes (forestry, agriculture or bushfires), a visual examination of each catchment was performed with Google Earth. Several catchments were deemed to have high potential for land-use signals in the streamflow data, and so were excluded. In total, 34 catchments remained (Figure 1). Of these, 14 lie on the eastern coast of New South Wales (NSW) outside the Murray–Darling Basin (MDB), and 20 lie within the MDB, principally in the southern MDB. The median year of streamflow data commencement is 1948.

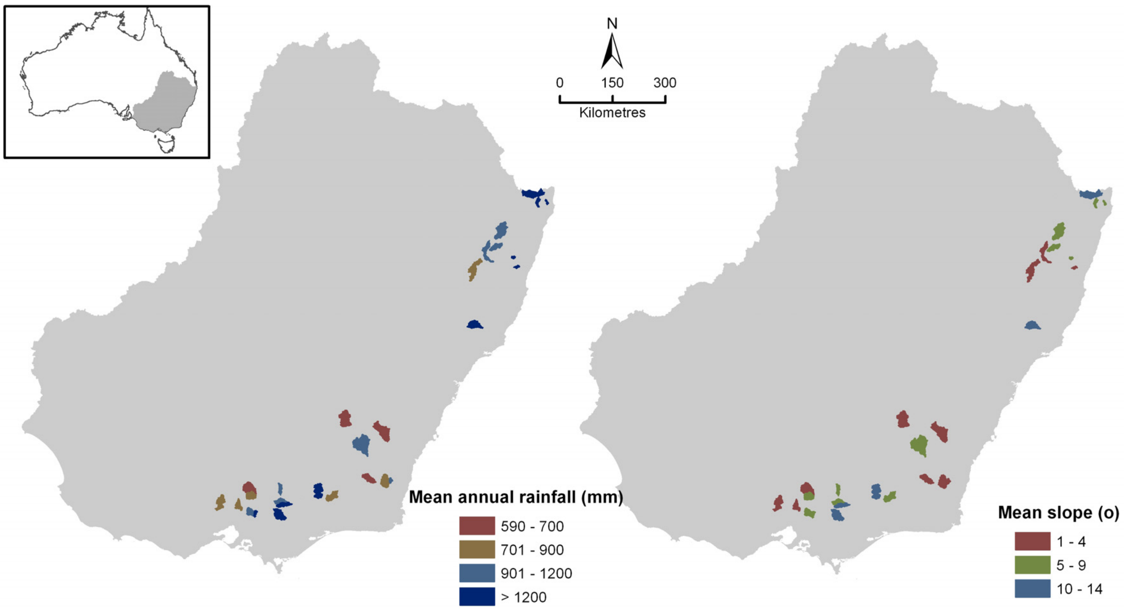

Figure 1 Mean annual rainfall (left) and mean slope (right)

2. METHOD

From the observed data the runoff, rainfall, runoff coefficient, percentiles of daily rainfall (P) and runoff (Q) were computed, and simple modelling was undertaken to evaluate slow-flow and quick-flow and hydrograph recession constants for each season and each year of observed records for each of the 34 catchments. The non-parametric Wilcox test was applied to the resulting seasonal and annual time series, to assess whether the median value of the above metrics were significantly different during the recent drought (1997–2008) compared to the prior period (pre-1997).

The task of separating baseflow (sub-surface flow) from river discharge data has many practical difficulties and a variety of methods exist. This study used the Lyne and Hollick digital filter (Grayson et al., 1996). While the quick and slow flow responses resulting from the application of this method have little physical meaning, the filter has been widely applied and there is a considerable body of data available for comparative purposes (e.g. Lacey, 1996, Petheram et al. 2008).

Because there was no groundwater data for these catchments, other techniques were employed to infer changes in groundwater behaviour. The analysis of flow recession curves enabled changes in the recession curve to be assessed and the groundwater reservoir to be characterised. Preliminary analysis indicated that the recession curves for many of these catchments exhibited non-linear behaviour. For this reason we used the non-linear model described by Wittenburg (1999) and shown in Equation 1:

$$Q_t = Q_0\left[1+\frac{(1-b)Q_0^{1-b}}{ab}t\right]^{\frac{1}{(b-1)}} \qquad (1)$$

Where Q_t is the streamflow at time t and Q_0 is the initial streamflow. The first step in this analysis was to identify suitable streamflow data pairs and group them by season and/or year. Data pairs were selected such that $Q_t>Q_{t-1}$ and that the total catchment average rainfall on the two preceding days was <1 mm. The parameter *b* in Equation 1 was set to 0.5 based on the results from theoretical and experimental studies (Wittenberg, 1999). Parameter *a* in Equation 1 was then optimised to each set of data pairs in each season/year. Wittenberg (1999) argues that even if the ‘true’ value of b is not exactly met, the assumption of b=0.5 would be more physically based and better fitting for the majority of river basins than the linear reservoir.

We also undertook rainfall-runoff modelling using the Sacramento model on 111 unregulated catchments across SEA (focusing on catchments in southern SEA). The Sacramento model was calibrated to the 1975-1996 period (calibration period) using a log-bias constraint (Viney et al. 2009) to ensure total flow volumes were well modelled and then independently tested on data during the recent drought (1997-2008).

3. RESULTS

3.1. Empirical and analytical analysis

Catchments in the northern part of the study region did not consistently exhibit a significant change in hydrological behaviour. For this reason all discussion will focus on the catchments in the southern half of the study region.

Figure 2 shows that all catchments in the southern half of SEA, bar one, exhibited a statistically significant reduction in median annual runoff during the drought and more than 80 percent of these catchments exhibited a statistically significant reduction in their median runoff coefficient. Three of the four high rainfall and high relief catchments (Figure 1) did not have a statistically significant change in the median runoff coefficient.

Figure 3 shows that statistically significant reduction in daily rainfall occurred between the 10th and 40th percentiles for all southern SEA catchments. A statistically significant difference was observed for daily runoff percentiles between 10th and 60th. Although only one catchment in southern SEA showed a statistically significant reduction in the 1st percentile of rainfall, all catchments except 2 of the 4 high rainfall high relief catchments (Figure 1) showed a statistically significant reduction in the 1st percentiles of daily runoff.

Figure 4 illustrates that slow-flow during the recent drought (1997 to 2008) was significantly different to the long term average ($p<0.05$) in all the catchments in southern SEA. Slow-flow declined in roughly the same proportion as total flow across all catchments in SEA (not shown); in part likely to be a function of the separation technique used.

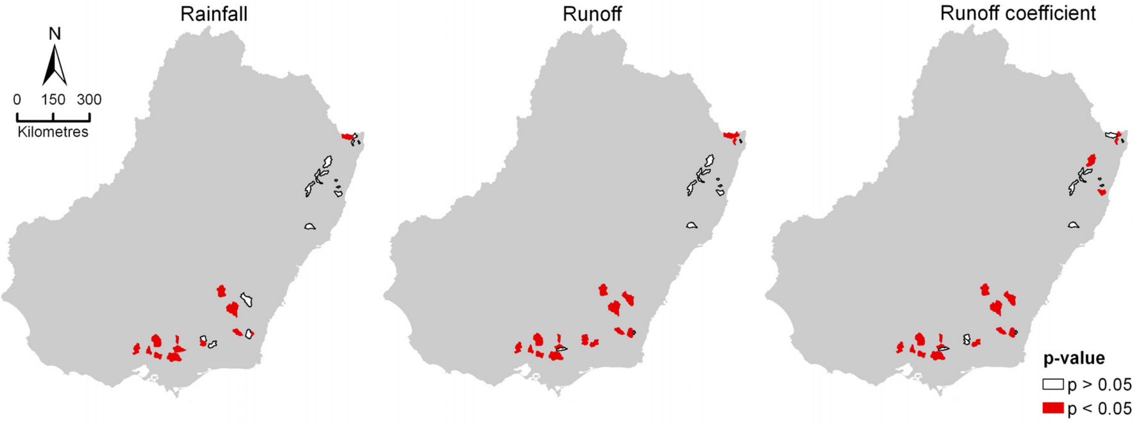

Figure 2 Statistically significant changes (reduction) in rainfall, runoff and runoff coefficient.

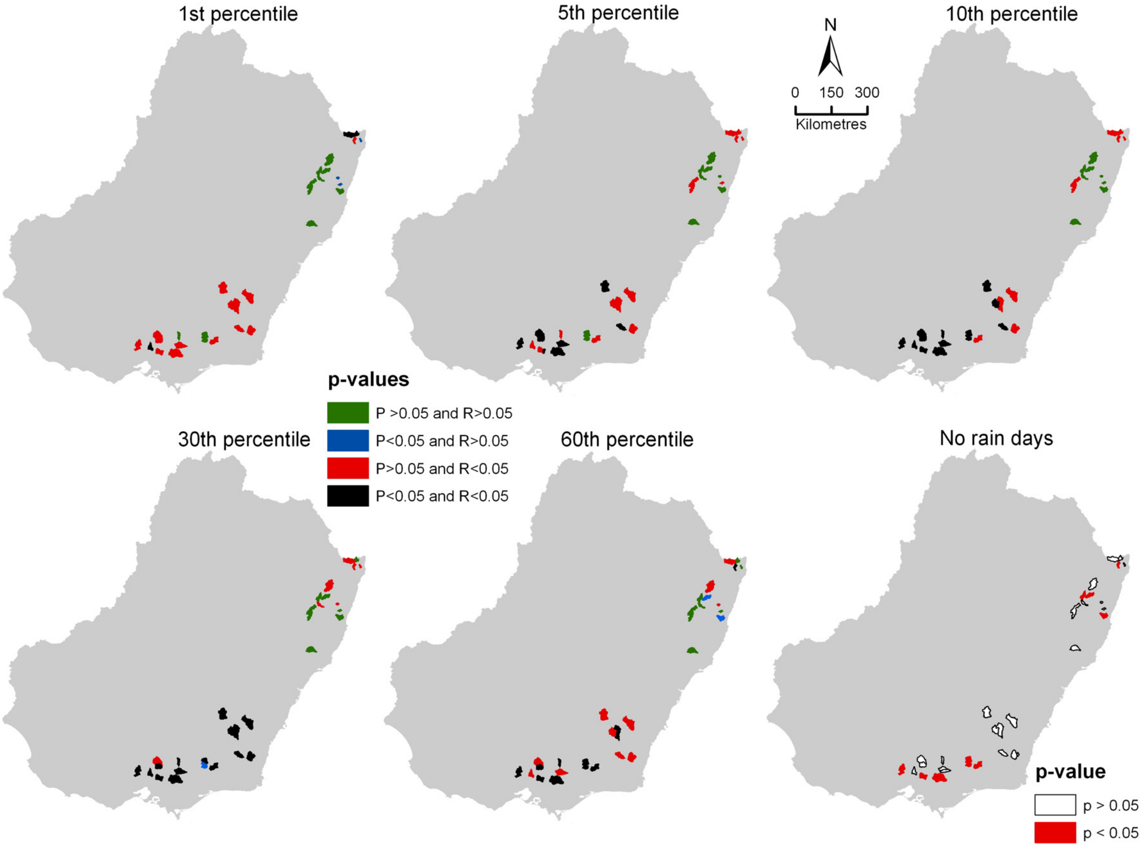

Figure 3 Statistically significant change (reduction) to 1st, 5th, 10th, 30th, 60th daily rainfall (P) and runoff (R) and statistically significant change to the number of no rain days.

More than 70 percent of catchments in southern SEA exhibited a statistically significant reduction in recession coefficient *a* i.e. Equation 1 (Figure 4). These results suggest that during the recent drought there was a change in the aquifer storage and outflow relationship of these catchments. Those catchments in Figure 4 that show a statistically significant change in slow-flow, but not in recession coefficient *a*, either have a very low or very high mean annual rainfall. In the low-rainfall catchments the recession coefficient is very low (much less than 1) indicating negligible surface water and groundwater connectivity and is most likely to be a result of bankflow return following an event. Approximately 40 percent of the catchments in southern SEA showed a statistically significant difference in the cease-to-flow metric (defined as the percentage of time daily flow was less than 0.1 ML) during the recent drought. All the catchments that had a statistically significant difference in the cease-to-flow metric had a low mean annual rainfall.

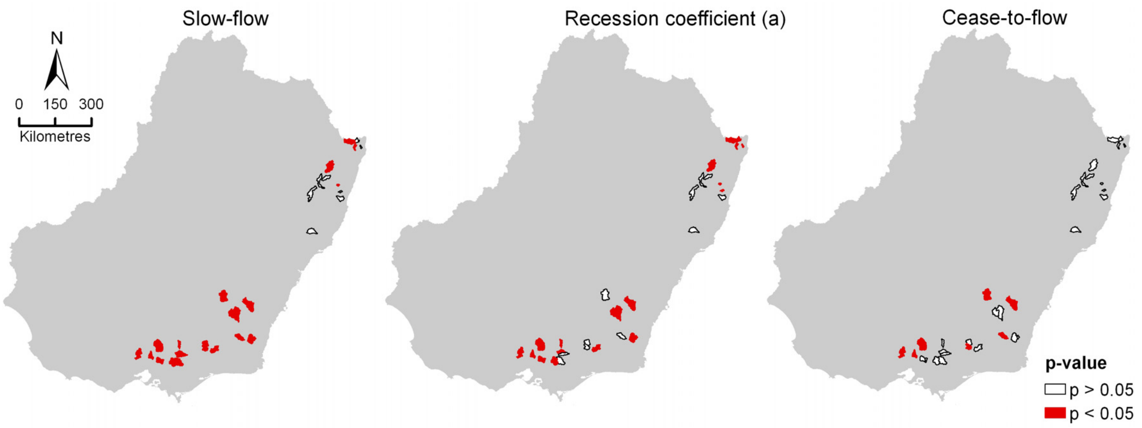

Figure 4 Statistically significant change to slow-flow, recession coefficient, cease-to-flow

3.2. Rainfall-runoff modelling

Rainfall-runoff modelling indicated that those catchments with the largest model bias during the drought were located in southern SEA (i.e. central Victoria and parts of southern NSW). Large positive biases provide support for the hypothesis that there has been an unexpectedly large decline in runoff during the drought. Unfortunately interpretation of the results is confounded by conceptual rainfall-runoff models typically not simulating low-flows as well as they simulate high flows and potential anthropogenic change (e.g. increase in farm dams). Both of these would cause a positive bias during the drought. Catchments in northern SEA and the high rainfall, high relief catchments in SEA had a model bias close to zero (Figure 5).

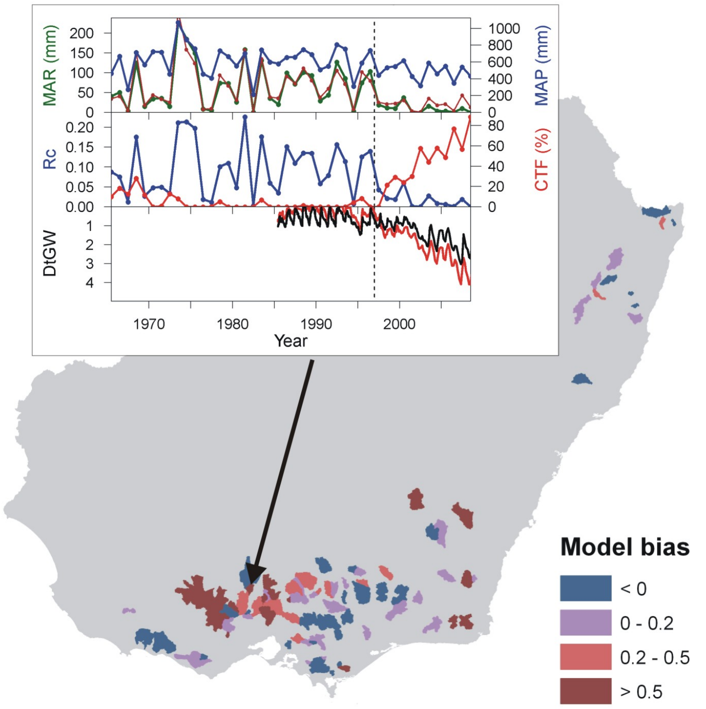

Figure 5 Model bias during the recent drought (1997-2008). Inset: Observed data from Axe Creek. Top: mean annual runoff (MAR) in green, mean annual rainfall (MAP) in blue, modelled annual runoff (MAR) in brown. Middle: runoff coefficient (Rc) in blue and cease to flow (CTF) in red. Bottom: depth to groundwater (DtGW). Vertical dashed line indicates start of recent drought.

4. DISCUSSION

A consistent pattern that emerged was that in southern SEA the catchments with moderate rainfall (i.e. 600 to 900 mm) and low-relief consistently showed statistically significant reductions in runoff coefficient and daily runoff percentiles during the drought, while the high rainfall, higher-relief catchments did not. Yet all catchments in southern SEA experienced a similar reduction in mean annual rainfall during the drought (~17 to 22 percent).

A statistically significant reduction in very high runoff percentiles (1st percentile) during the drought without a corresponding reduction in very high daily rainfall percentiles (Figure 3) may be the result of a change in factors controlling conditions under which saturation runoff occurs, particularly as these catchments are relatively small in size (<1250 km^2). The observation that statistically significant reduction in 1st percentiles of daily runoff only occurred in 2 of the 4 high rainfall high relief catchments suggests that factors controlling the generation and organisation of areas of saturation in these catchments may not have notably changed.

One of the challenges in trying to determine whether there has been a change in dominant hydrological behaviour is the non-linear relationship between rainfall and runoff, largely due to spatial and temporal variations in antecedent moisture conditions (AMC). To address this non-linearity in runoff, a number of researchers have tried to develop AMC indexes (e.g. Ali and Roy 2010), using mainly temporal windows of less than 1 month to characterise catchment AMC. The Soil Conservation Service Curve Number approach is probably the most widely used method for computing runoff at the plot scale. This method, however, uses only a 5 day temporal window to characterise AMC, and studies that have tested longer temporal windows have not provided more robust relationships (Silveria et al. 2000). These studies indicate that there is a limit to how dry a soil column can become, and hence how much it can contribute to hydrological persistence. To invoke hydrological persistence over an inter-annual timeframe (as we believe we are seeing in the moderate rainfall, low relief catchments of southern SEA) requires a change to a hydrological state operating over longer timescales, such as groundwater. Recession curve analysis suggested that in the moderate rainfall, low-relief catchments of southern SEA there was indeed a change in the behaviour of groundwater systems underlying these catchments and that this is consistent with observations from piezometers in dryland areas of central Victoria, which showed a steady decline in groundwater level during the recent drought (e.g. inset in Figure 5).

For these catchments it is thought that shallow groundwater levels amplified runoff during pre-drought conditions by reducing the depth of the unsaturated zone (i.e. variable source area concept) and facilitating organised patterns of drainage and connection of source areas of runoff as the soil wetted up during a rainfall event. Grayson and Blöschl (2000) showed that the runoff response in a catchment is quite different under conditions of organised soil moisture versus random soil moisture. Under a falling watertable, the storage capacity of the unsaturated zone increases, saturation conditions are less likely to occur, and the connectivity of source areas is likely to be less organised.

In the high relief, high-rainfall catchments, falling groundwater levels will result in a reduction of groundwater baseflow to streams, which we observed to show a statistically significant reduction in slow-flow for all catchments across southern SEA. However, in these catchments we contend that, due to the higher relief of these catchments, groundwater levels do not act as a major control over the formation of areas of saturation and the organisation of soil moisture during an event. Rather, the formation of areas of saturation and the connectivity of source areas will be predominantly controlled by the high rainfall. Potter et al. (2011) found that annual rainfall and temperature were sufficient to explain the reduction in runoff in these high relief, high rainfall catchments (i.e. there was negligible unexplained residual in these catchments).

Although none of our study catchments were located in low-rainfall zones (300-500mm) it is contended here that catchments in low rainfall zones would be unlikely to have experienced a change in hydrological behaviour, because elevated groundwater levels are unlikely to have occurred prior to the drought. Finally it is worth noting that many of the catchments that experienced the largest reductions in runoff, exhibited dryland salinity. Elevated saline groundwater levels would impact negatively on vegetation health, reducing leaf area index, and hence reducing transpiration and interception loss. Had the groundwater been fresh, leaf area index would have been higher, increasing transpiration and interception loss and hence reducing the amplification of runoff during the pre-drought conditions.

5. CONCLUSIONS

The hydrological behaviour of low-relief, moderate-rainfall catchments in southern SEA changed during the recent drought. Supporting lines of evidence for this are:

- There was a statistically significant reduction in runoff coefficients and daily runoff percentiles in catchments in southern SEA and cease-to-flow in many ephemeral catchments has increased.
- Very high daily rainfall percentiles (i.e. 1st percentile) during drought were not found to be statistically different from those prior to the drought, but the moderate-rainfall low-relief catchments of southern SEA exhibited a statistically significant reduction in the 1st percentile of daily runoff.
- Conceptual rainfall-runoff models calibrated between 1975 and 1996 simulated runoff in the years prior to 1975 well, but significantly overestimated runoff over the course of the drought.

- There was a statistically significant reduction in slow-flow.
- These catchments exhibited a statistically significant change (reduction) in recession coefficient, suggesting that during the recent drought there was a change in the aquifer storage and outflow relationship.

No consistent change in hydrological behaviour was observed for the catchments in northern SEA or the high-rainfall high-relief catchments in southern SEA.

It is thought that the mechanism by which groundwater amplified runoff during pre-drought conditions in the moderate-rainfall, low-relief catchments in southern SEA was through a reduction in storage capacity of the unsaturated zone and by facilitating organised patterns of drainage and the connection of source areas of runoff as the soil wetted during a rainfall event (i.e. variable source area concept). It is contended that in the higher relief catchments of southern SEA, groundwater levels do not act as a major control over the formation of areas of saturation and the organisation of soil moisture during an event. Rather the formation of areas of saturation and the connectivity of source areas in these catchments is predominantly controlled by the high rainfall.

The high rainfall over the spring/summer of 2010-11 will allow us to examine whether the pre-drought rainfall-runoff relationship has re-established. During drought conditions farm dams will intercept a greater proportion of flow than during wet conditions. Future investigations will also focus on the role of farm dams in contributing to the unexpected decline in runoff during the drought. Understanding how catchments behave in times of drought may provide insights into how best to adapt hydrological models to better simulate runoff under drier climates.

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