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Drought, groundwater storage and stream flow decline in southwestern Australia

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[1] In this study we examine the hydrological processes that underpin non-stationarity in hydrological prediction. This is achieved by analysis of linkages between rainfall, groundwater storage, and runoff in Southwest Western Australia (SWWA), a region experiencing stream flow decline since the mid-1970s. We find a close connection between rainfall and changes in catchment groundwater storage, with increases in storage in years with annual rainfall above a threshold (1050–1400 mm), and declines during low rainfall years. Where groundwater is in contact with the stream bed, runoff, as a proportion of rainfall, is highly correlated with groundwater storage. Recent drought years have reduced groundwater storage and runoff ratio. In the absence of replenishing wetter years, lower runoff ratios are subsequently maintained. Runoff from a given depth of annual rainfall is now far lower than that produced 15 years ago. In this way groundwater storage acts as the catchment's "memory". This study highlights the importance of catchment groundwater storage that may be used to improve runoff prediction in a drying climate. **Citation:** Hughes, J. D., K. C. Petrone, and R. P. Silberstein (2012), Drought, groundwater storage and stream flow decline in southwestern Australia, *Geophys. Res. Lett.*, *39*, L03408, doi:10.1029/2011GL050797.

1. Introduction

[2] A stationary time series is one for which the probabilistic behaviour of every collection of values is identical to that of any time shifted set [*Shumway and Stoffer*, 2006]. Confident prediction relies on an assumption of stationarity for model calibration and subsequent prediction. Non-stationarity is a widely acknowledged issue in hydrological prediction and is related to changes (and cycles) in climate [e.g., *Vaze et al.*, 2010] and land use [e.g., *Huang and Zhang*, 1997].

[3] Groundwater may be underrepresented as a variable in prediction of catchment response to climate change. Groundwater is an important source of stream flow from catchments [*Sklash and Farvolden*, 1979], but the role of groundwater storage on runoff (Q) production is not fully appreciated. For example, without explicit groundwater representation in rainfall-runoff models, prediction uncertainty was increased for south western Australia [*CSIRO*, 2009] where climate drying has been observed [*Petrone et al.*, 2010].

[4] Predictions of future water resource availability are a critical need. However, predictions are difficult where there may be a transition in climate and related conceptualisation of the hydrological processes [*Milly et al.*, 2008; *Merz et al.*, 2011]. Although groundwater recharge and watertable levels are sensitive to climate variability in many regions [*Allen and Ingram*, 2002; *Hayhoe et al.*, 2007; *Hodgkins et al.*, 2003], the impact of long-term climate change on groundwater is not well understood and few studies have examined how the connection between groundwater and surface water (GW-SW) may influence long-term runoff trends.

[5] Runoff from the Darling Range in southwest Western Australia (SWWA) supplies a significant proportion of the total water supply of Perth, Western Australia (36% in 2007, [*Western Australia Water Corporation*, 2008]). However, since the mid 1970s stream yields from metropolitan drinking water catchments have shown a continued decline related to an overall rainfall reduction [*Bates et al.*, 2008]. Furthermore, an increase in the occurrence of drought years in the last decade that has led to a systematic drop in runoff ratio (Q/P) over this time and a change in low flow conditions suggesting a new hydrologic state has been reached [*Petrone et al.*, 2010].

[6] In this study, we use long-term records of rainfall, groundwater and streamflow, to examine the mechanisms for streamflow decline in the Darling Range of SWWA that serve as Perth's main surface water supply. In particular we examine, (i) the link between groundwater storage and runoff, and (ii) the relationship between rainfall and groundwater storage, and thereby the role that groundwater level has in controlling the rainfall-runoff relationship.

2. Site

[7] The Darling Range is a North - South ridge of ~300 m in elevation, 20 km inland from the coast of south–western Australia with 14 reservoirs that serve as the surface water supply for the Perth metropolitan area. Vegetation is dry sclerophyllous forest. The climate is Mediterranean with 80% of annual rainfall between May and October. Annual rainfall is greatest on the western margin of the range (>1100 mm), and decreases to the east and north (900–1100 mm). The regolith is around 30 m deep, with a surface gravelly layer of 1–10 m depth. Land use is primarily logging of the native forest for timber with some areas subject to bauxite mining. Very little of the water supply catchments have been permanently cleared of forest. There are no significant quantities groundwater extraction in the Granite bedrock areas of the Darling Range.

3. Methods

[8] A total of nine catchments were selected for analysis (Figure 1). Stream flow data were available from the Western Australian Department of Water (DoW) for all catchments

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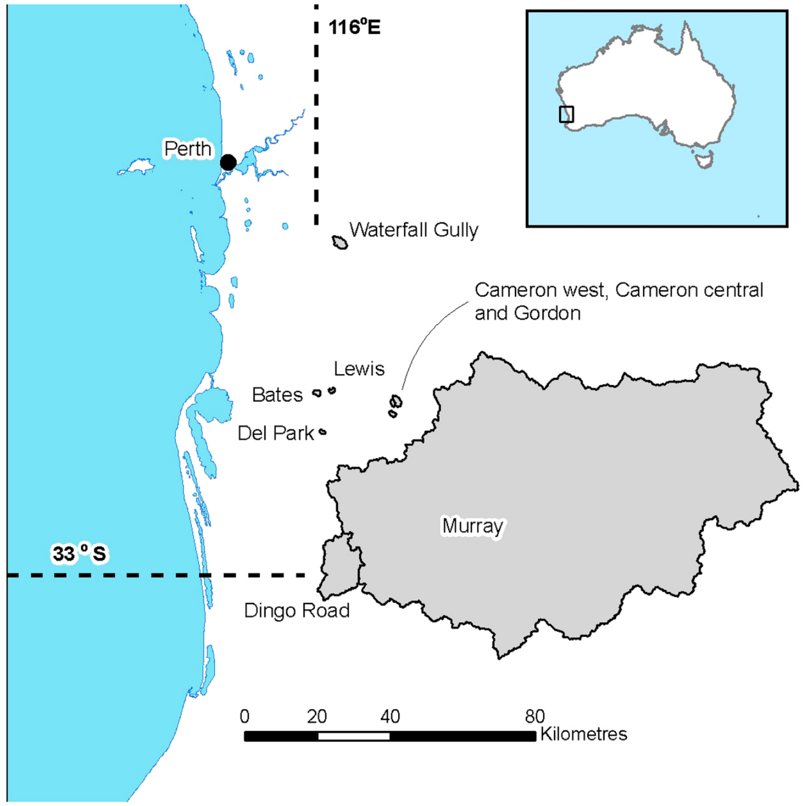

Figure 1. Study area showing research catchments.

up to and including 2009. Interpolated rainfall data were obtained from the SILO data drill (http://www.longpaddock.qld.gov.au/silo) to the nearest twentieth of a degree of the stream gauge site. Long-term GW data were available for six catchments (Table 1), collected manually at an approximate time interval of four weeks by Alcoa of Australia Limited (Alcoa). Bores were selected that were free of errors and had a time series of length at least 75% of the stream flow monitoring period. No data from shallow, perched groundwater (screened <5 m below the ground surface) were used in this analysis. The number of bores used in each catchment are listed in Table 1. Four catchments have had a proportion mined for bauxite (Table 1) and rehabilitated within the monitoring period. Bauxite mining involves clearing of portions of the catchment before mining to a depth of around 4 metres. Mine pits are rehabilitated with a similar species mix to the pre-existing forest. Rehabilitation usually takes place within 2–3 years of mining. For more information on the mining/rehabilitation process see *Koch* [2007].

Table 1. Characteristics of Study Catchments

Catchment	AAR[a] (mm)	Area (km^2)	Proportion Mined	Bores Used	Mean Riparian DTW[b] (m)	Annual Rainfall at ΔDTW = 0 (mm/year)	P Statistic (ΔDTW–Rain)	DTW–Runoff Ratio ρ
Bates	1205	2.23	0	8	2.3	1313	0.024	0.90
Lewis	1179	2.01	0.5	41	2.6	1286	0.034	−0.76
Del Park	1205	1.33	0.31	44	1.3	1383	0.006	−0.93
Cameron West	989	1.87	0.06	33	12.1	1556	0.373	−0.20
Cameron Central	989	4.73	0.24	33	8.6	1224	0.072	−0.21
Gordon	975	2.13	0	20	11.4	1410	0.048	−0.13
Catchment	**AAR[a] (mm)**	**Area (km^2)**	**Proportion Mined**	**Bores Used**	**Mean Riparian DTW[b] (m)**	**Annual Rainfall at ΔS = 0 (mm/year)**	**P Statistic (ΔS–Rain)**	**S–Runoff Ratio ρ**
Bates	1205	2.23	0	NA	NA	1216	0.084	0.87
Waterfall Gully	1052	8.6	0	NA	NA	1056	<0.001	0.86
Dingo Road	1048	147.2	0	NA	NA	1051	<0.001	0.74
Murray	1020	6757.6	<0.05	NA	NA	1031	0.001	0.65

[a]Average annual rainfall since 1969.
[b]Long term groundwater dip average from any stream zone piezometers within 5 m elevation difference of the stream.

[9] Estimates of catchment annual minimum GW storage (*S*) for the catchments without groundwater measurements (Table 1) were obtained using the method of *Brutsaert* [2008]. The four catchments selected have perennial streams, and were relatively free from changes in land use during the monitoring period. *S* represents annual minimum catchment GW storage that is able to be a source of water to the stream. Any groundwater stored within the catchment when the stream is not flowing will not influence the estimate of *S*. Briefly, the calculation of *S* involves determining the lowest daily flow rate ($Q_{\min}$) in each year, assuming this "baseflow" is due only to groundwater discharge, and that the catchment behaves as a linear storage. Such a reservoir model has the discharge characteristic with an exponential decay:

$$y = y_0 \exp(-t/K) \quad (1)$$

where y is discharge [L], y_0 is its value at the chosen reference time, i.e., t = 0, and K is the characteristic time scale of the catchment drainage process [T]. K is determined for each catchment by creating a master recession curve for each catchment and fitting equation (1) to that curve. This allows calculation of *S*:

$$S = KQ_{\min} \quad (2)$$

where *S* is the estimated annual minimum groundwater storage above the stream no flow point. Annual change in minimum catchment storage (ΔS) was compared to annual rainfall to determine thresholds required to maintain, decrease or increase *S*. Runoff generally follows an annual cycle with minimum in autumn before the onset of winter rain and maximum levels in spring. To best capture this pattern, annual rainfall was calculated for the July to June period each year, thus minimum annual *S* is easily compared with the previous 12 months rainfall. Such a period reduces the effect of anomalies created by heavy rains late summer or early autumn in some years. Linear regression was used to test the significance of the correlation between annual rainfall and ΔS.

[10] The riparian zone is defined as being the area adjacent to the stream bed whose ground surface elevation was within 5 m elevation of the stream bed. Examination of catchment topographic maps suggested that the figure of 5 m would reasonably delineate the riparian zone from hillslopes. Riparian Depth to Water (DTW) was calculated using bores within this zone. Riparian DTW has been calculated since it is assumed that this statistic relates to surface water - groundwater connection better than catchment average DTW alone. This relates to the importance of the riparian zone in efficiency of runoff generation processes.

[11] Catchment average annual DTW was obtained by:

1. Interpolating the time series of measurements for each bore to produce regular data and taking the annual mean. This reduces the bias created by irregular observations.

2. Spatially interpolating the annual mean DTW for all bores within each catchment to produce a regular grid within the convex hull of the bore locations for each year. DTW was calculated as the mean of the grid values for that year. This reduces the bias created by irregularly positioned bores. Spatial interpolation was conducted using the method of *Akima* [1978], within the R software package "Akima" (http://cran.r-project.org/web/packages/akima/akima.pdf).

[12] Runoff ratio was calculated for those catchments where DTW data were available. Runoff ratio (Q/P) is the annual total runoff (Q - mm) as a proportion of rainfall for that year (P - mm). Correlations between runoff ratio and DTW or *S* were calculated using the non-parametric Spearman's correlation coefficient, defined as:

$$\rho = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}} \quad (3)$$

where ρ is the Spearman correlation coefficient, and x_i and y_i are the two data vectors converted to rank order. Non-parametric correlation is used in the analysis of the DTW/S – runoff relationship due to its non-linear nature. Conversely, linear regression is used for the analysis of the P – DTW/S relationship since it is linear in nature and allows for estimation of thresholds by extrapolation.

[13] Clearing for mining will obviously affect the relationship between DTW and rainfall. Where catchments were cleared for mining, the years from clearing to the third year of rehabilitation were not considered in the analysis of the DTW – rainfall relationship.

4. Results

[14] Groundwater data show a declining trend at all sites over the monitoring record (Figure 2), with rates of decline ranging from 0.05–0.48 m.year^{-1}. Bore hydrographs typically show their largest declines following drought years (e.g., 2001 and 2006). Similar trends were observed in the catchment storage (*S*) estimates (not shown here).

[15] Catchment annual average DTW and runoff ratio is strongly correlated in catchments where the DTW is <3.0 m within the riparian zone (Table 1 and Figure 3) defined as areas within 5 m elevation of the stream bed. These catchments will be termed as "groundwater connected" hereafter, reflecting the contact between groundwater and the ground surface. Where DTW was >3.0 m in the riparian zone, no such correlation existed (Table 1). Hereafter, these catchments will be termed "groundwater disconnected". Runoff ratio in groundwater disconnected catchments (Cameron West, Cameron Central and Gordon) was always less than 0.03, with a mean of less than 0.01. These catchments do not show a temporal trend in runoff ratio.

[16] Groundwater connected catchments showed a step decline in runoff ratio and increase in catchment average DTW following drought years (annual rainfall <900 mm). In the absence of very wet years (>1300 mm), DTW and runoff ratios were maintained in subsequent years. Drought effects are evident in the Bates catchment (inset, Figure 3) where the drought years 1994 and 2001 caused large reductions in runoff ratio and increase in catchment average DTW (relative to prior year), moving the catchment state to a lower runoff regime in each case (down and to the left in Figure 3).

[17] Linear correlation between change in annual mean DTW and annual rainfall was significant (P values <0.05) for Bates, Lewis, Del Park and Gordon catchments (Figure 4), with regression slopes of -1.3, -1.8, -1.2, and -0.01 mm DTW change per mm of rainfall respectively. The annual rainfall threshold at which no change in DTW is expected (from linear model ΔDTW = f(Annual rainfall)) ranged from 1286–1410 mm (Table 1).

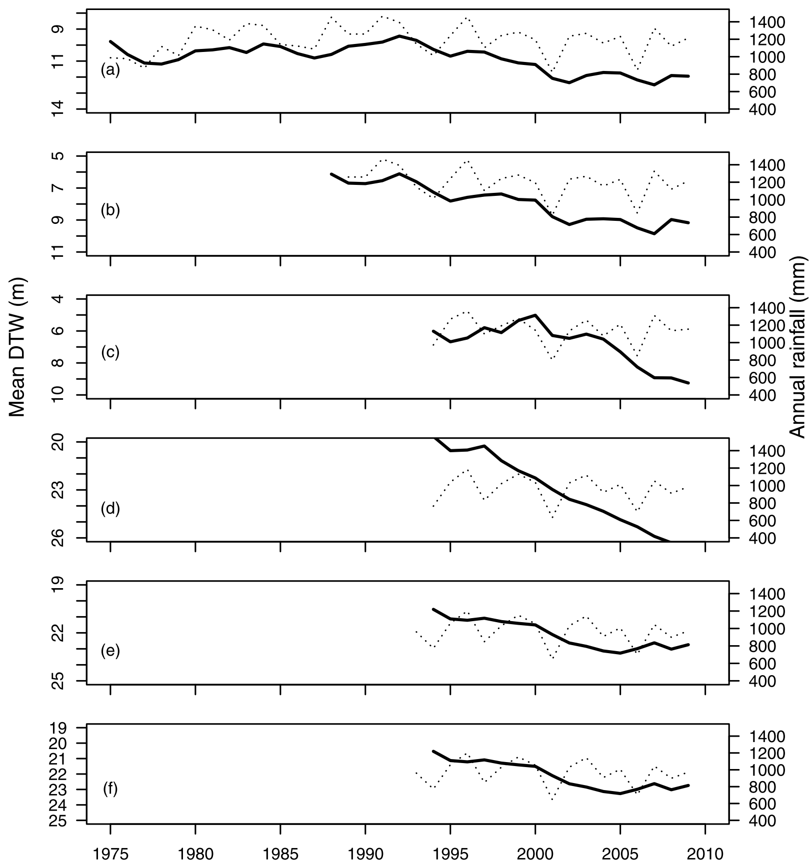

Figure 2. Annual mean catchment depth to water (solid line), and annual rainfall (broken line) in research catchments with a piezometer network; (a) Del Park, (b) Bates, (c) Lewis, (d) Gordon, (e) Cameron West and (f) Cameron Central.

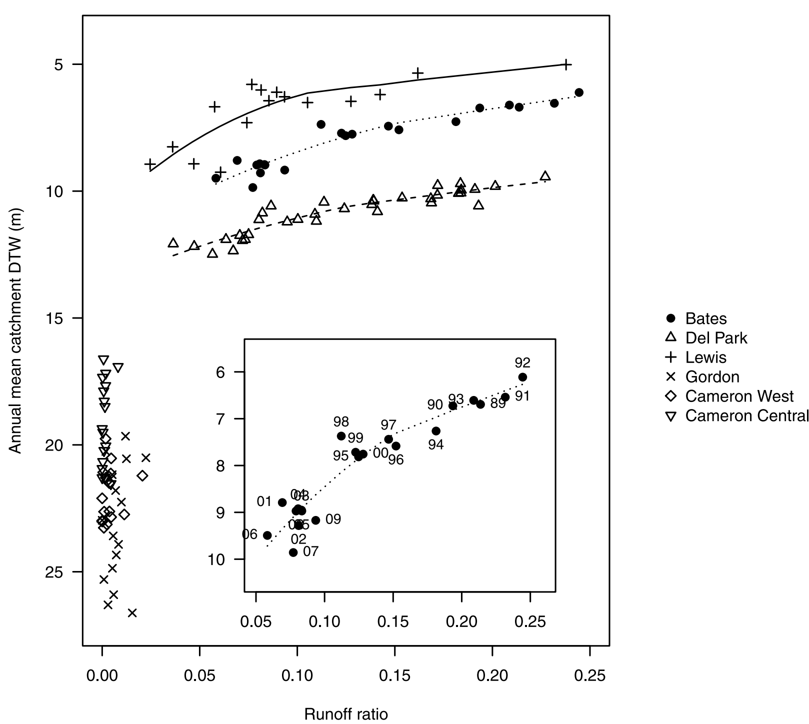

Figure 3. Relationship between annual mean catchment depth to water and annual catchment runoff ratio. Inset shows Bates data in detail and plot legend. Data point labels indicate year.

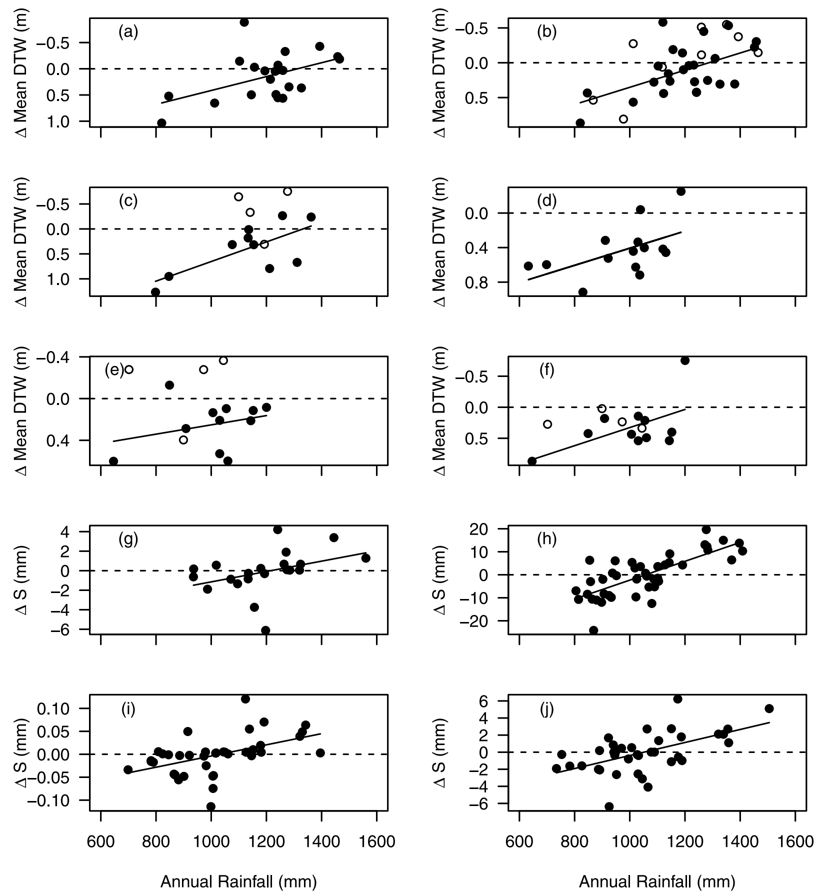

Figure 4. Relationship between change in annual mean catchment depth to water (ΔDTW) or change in estimated catchment storage (ΔS) with annual rainfall at (a) Bates - ΔDTW, (b) Del Park, (c) Lewis, (d) Gordon †, (e) Cameron West, (f) Cameron Central (g) Bates - ΔS, (h) Waterfall Gully, (i) Murray and (j) Dingo Road. Open symbols refer to years in which catchments were mined and the first three years of mine rehabilitation. These data are not included in the line of best fit estimation. † Gordon rainfall was shifted forward by one year to account for a significant 1 year rainfall - DTW lag.

[18] Using catchment storage (S) estimated from runoff data, linear regression between ΔS and rainfall (Figures 4g–4j) showed that in general, rainfall is a significant factor in explanation of ΔS (Table 1). Threshold rainfall to maintain groundwater storage exceeds average annual rainfall in all cases, hence falling groundwater levels in all catchments. Threshold rainfall (above which ΔS rises), ranges from 1031 to 1216 mm per annum. In the case of Bates catchment, the ΔS threshold rainfall is approximately 100 mm lower than that obtained using observed groundwater data (1216 vs. 1312). Therefore rainfall thresholds derived from ΔS may be an underestimate of true groundwater-rainfall threshold. It is thought that difference is due to the nature of the DTW and S statistics. More specifically, S is derived from a single point of low flow each year, while DTW represents a temporally weighted average across the whole year. Much of the groundwater that influences the DTW measurement will be used by vegetation or be returned as stream flow by the time the corresponding low flow measurements used for S are made in autumn.

5. Discussion

[19] Our study demonstrates that groundwater storage and streamflow in the Darling Range are strongly linked, and are highly non-linear. Runoff is highly correlated with groundwater storage when the watertable is close to the soil surface in the riparian zone, indicating its critical importance for streamflow generation. This corroborates the findings of *Turner et al.* [1987], who estimated that the vast majority of stream flow generation was from groundwater of a moderate residence time (up to 50 days). Further, our analysis shows that groundwater storage can change rapidly with extremes in annual rainfall and this storage is carried forward in subsequent years when rainfall may be close to average. Thus, groundwater acts as a catchment "memory", storing the cumulative difference between rainfall and actual evapotranspiration from previous years, with a long term impact on runoff ratio.

[20] The threshold rainfall required to maintain groundwater storage varies depending upon location and method of groundwater storage estimation. It is likely that forest management and forest density will influence the threshold in each individual location. Additionally, the threshold rainfall may be changing with time in response to management or climate change. These issues may need to be addressed if this approach is to be extended. The groundwater storage – rainfall relationship exhibits rainfall thresholds, with an annual rainfall of greater than 1050–1400 mm required to measurably increase GW storage. When rainfall is significantly below

this threshold, storage falls. The combination of these two relationships across drought periods leads to changing rainfall-runoff relationships as was observed by *Petrone et al.* [2010].

[21] The rainfall and runoff time series data of south-western Australia through the last 30 years do not satisfy the conditions of a stationary time series, making prediction difficult [*Petrone et al.*, 2010]. This study shows that the addition of groundwater storage information brings new insight to non-stationary runoff time series. Hydrologic observations during shifts in climate also provide an opportunity to improve our understanding of processes that amplify the runoff response to rainfall. Such opportunities are not apparent during more "stationary" periods. Explicit representation of groundwater storage, particularly the connection of permanent groundwater to the riparian zone, will almost certainly improve prediction in hydrologic models. Here we show that drought can have persistent effects on groundwater storage and runoff, in the absence of replenishing wetter years, that may be a challenge to traditional modelling approaches.

6. Conclusions

[22] Groundwater storage is the primary influence on runoff generation in the Darling Range of Western Australia. Where permanent groundwater levels fall below the stream bed throughout the year, catchment runoff as a proportion of annual rainfall does not exceed 0.03. Where the groundwater remains connected to the stream bed, runoff ratio is strongly correlated to groundwater storage. In this study, hydrological behaviour appears to be relatively simple with detectable connections between rainfall, groundwater storage and runoff. Groundwater stores show the effects of unusually wet or dry years and carry those effects forward in time; although within the data period there were no especially wet years. Particularly dry years resulted in systematic and persistent reductions in runoff ratios. Accordingly, it is proposed that the data presented in Figure 3 form the basis for a generalised GW storage – runoff relationship that may be of benefit to land management policy of south-western Australia, and should in principle be applicable in any catchment where groundwater storage influences stream flow.

[23] **Acknowledgments.** Acknowledgement and thanks must go to all those at Alcoa, The Western Australian Department of Water, the Water Corporation, CSIRO and elsewhere who had the foresight to implement long term stream and groundwater data collection projects, upon which this study relies. The authors appreciate the assistance provided by the Western Australian Water Foundation through project 041-05. The views expressed are not necessarily the views of the Government of Western Australia, nor the Water Foundation.

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