Government of **Western Australia**
Department of **Water**

Rainfall-runoff relationships for Darling Range water supply catchments in 2007

Looking after all our water needs

Salinity and land use impacts series

Report no. SLUI 59
September 2012

Rainfall–runoff relationships for Darling Range water supply catchments in 2007

by

Keren Raiter

Department of Water
Salinity and land use impacts series
Report no. SLUI 59
September 2012

Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone	+61 8 6364 7600
Facsimile	+61 8 6364 7601
National Relay Service 13 36 77
www.water.wa.gov.au

ISSN 1449-5252 (online) ISBN 978-1-921907-13-5 (online)

Recommended reference

Raiter, K 2012, *Rainfall–runoff relationships for Darling Range water supply catchments in 2007*, Salinity and land use impacts series, Report no. SLUI 59, Department of Water, Perth.

Acknowledgements

The Department of Water thanks the following for their contribution to this publication: John Ruprecht, who championed this report; Ken McIntosh and Mark Pearcey for guidance; Joanne Gregory, Tanya Brown, and from the Water Corporation, Charles Jeevaraj and Amanda Reed for supplying data and valuable advice; and Alex Waterhouse for editing. The author acknowledges Ken McIntosh, Melinda Burton, John Ruprecht, and Keith Barrett whose reviews improved this report:

For more information contact:
Tim Sparks
Resource Recovery, Department of Water
Telephone	+61 8 6364 7819
http://www.water.wa.gov.au

Cover photograph: *Autumn rain clouds brewing over the Darling Range water supply catchments*
Photo: K Raiter

Disclaimer

Contents

Appendices

Figures

Tables

Summary

The hydrology of the Darling Range water supply catchments in south-west Western Australia is undergoing systemic change, following a sharp decline in rainfall and runoff that took place in the mid 1970s and ongoing declines in runoff coefficients. Some rainfall-related variables are examined for a specific year – 2007 – to identify climatic factors that may have contributed to the well-below-average streamflow into the Darling Range water supply reservoirs that year despite above-average wet season rainfalls[1].

In 2007, wet season rainfall of 998 mm exceeded the 1975–2008 average by 14%, but the 110 GL of runoff from the Darling Range water supply catchments was 28% short of the average.

This qualitative assessment concludes that the following factors probably contributed to the low runoff coefficients observed in 2007:

- The new rainfall-runoff relationship observed in the recent decade
- Less intense, longer duration rainfall in 2007 compared to the 1975–2008 average
- The lag effect of the previous year's low rainfall (one of the driest on record)

The seasonality of rains and dry mid winter periods probably did not contribute to low runoff in 2007 relative to the 1975–2008 period average. Changes in vegetation cover and temperature were not investigated here, although they may also have affected 2007 runoff.

The decline in runoff coefficients observed in the recent decade is associated with declining groundwater levels. Groundwater levels have declined since 1975, and particularly in the last decade, due to the emerging deficit between rainfall (which has declined) and evapotranspiration (which has not declined to the same extent, and in some cases, has increased). This has led to less recharge and, in some cases, more uptake of groundwater by vegetation.

Where groundwater levels decline to the extent that they disconnect from stream zones, streamflow decreases in three ways: groundwater no longer discharges into streams (and instead some streamflow may be lost to the surrounding soil matrix); saturated areas, which would normally produce direct overland flow, contract; and throughflow (which is strongly influenced by groundwater levels and may be a dominant source of streamflow) declines.

The hydrology of the water supply catchments may not yet have reached equilibrium, and both groundwater levels and runoff coefficients may continue to decline, unless future rainfall is significantly higher than that of recent years, or evapotranspiration declines significantly.

---

[1] Relative to 1975–2008 records for the period May to October measured at Jarrahdale

1 Introduction

1.1 Report objective

The objective of this report was to investigate rainfall-related factors contributing to the well-below-average streamflow observed in the Darling Range water supply catchments in 2007, despite above-average wet season rainfalls[2].

1.2 Scope

Observed rainfall and runoff data from the twelve northern catchments that lie in the Darling Range and supply Perth and the Integrated Water Supply Scheme (IWSS) were evaluated for trends that may explain the below-average runoff in 2007. The catchments were: Bickley, Canning, Churchman, Conjurunup, Helena, Lower Helena, North Dandalup, South Dandalup, Serpentine Dam, Serpentine Pipehead, Victoria, and Wungong. The Stirling, Samson and Wokalup catchments were not included in this study.

1.3 Description of catchments

Location and climate

These catchments lie on the western margin of the Darling Plateau, to the east and south-east of Perth (Fig. 1). They cover most of the northern jarrah forest. The landscape is extensively laterised, with an average elevation of 300 m AHD and a combined area of 3768 km².

The climate of the catchments is classified as temperate (Stern et al. 2000), with hot dry summers and cool wet winters. Average annual rainfall ranges from about 500 mm in the north-east to 1050 mm in the south-west[3]. The average annual wet season (May to October) rainfall for Jarrahdale (considered to be representative of the Darling Range water supply catchments; Jeevaraj pers. comm. 21.01.2009), was 874 mm for the period 1975–2008.

A sharp decrease in winter rainfall occurred in the mid 1970s. The Indian Ocean Climate Initiative (IOCI) has described this change not as a gradual decline but more of a switching into an alternative rainfall regime. The rainfall decrease was only observed in early winter (May–July). Late winter rainfall has actually increased, although by a smaller amount, since 1975 (IOCI 2002).

---

[2] Relative to 1975–2008 records, for the period May to October measured at Jarrahdale

[3] 1975–2003 averages, based on rainfall isohyets produced by Department of Water

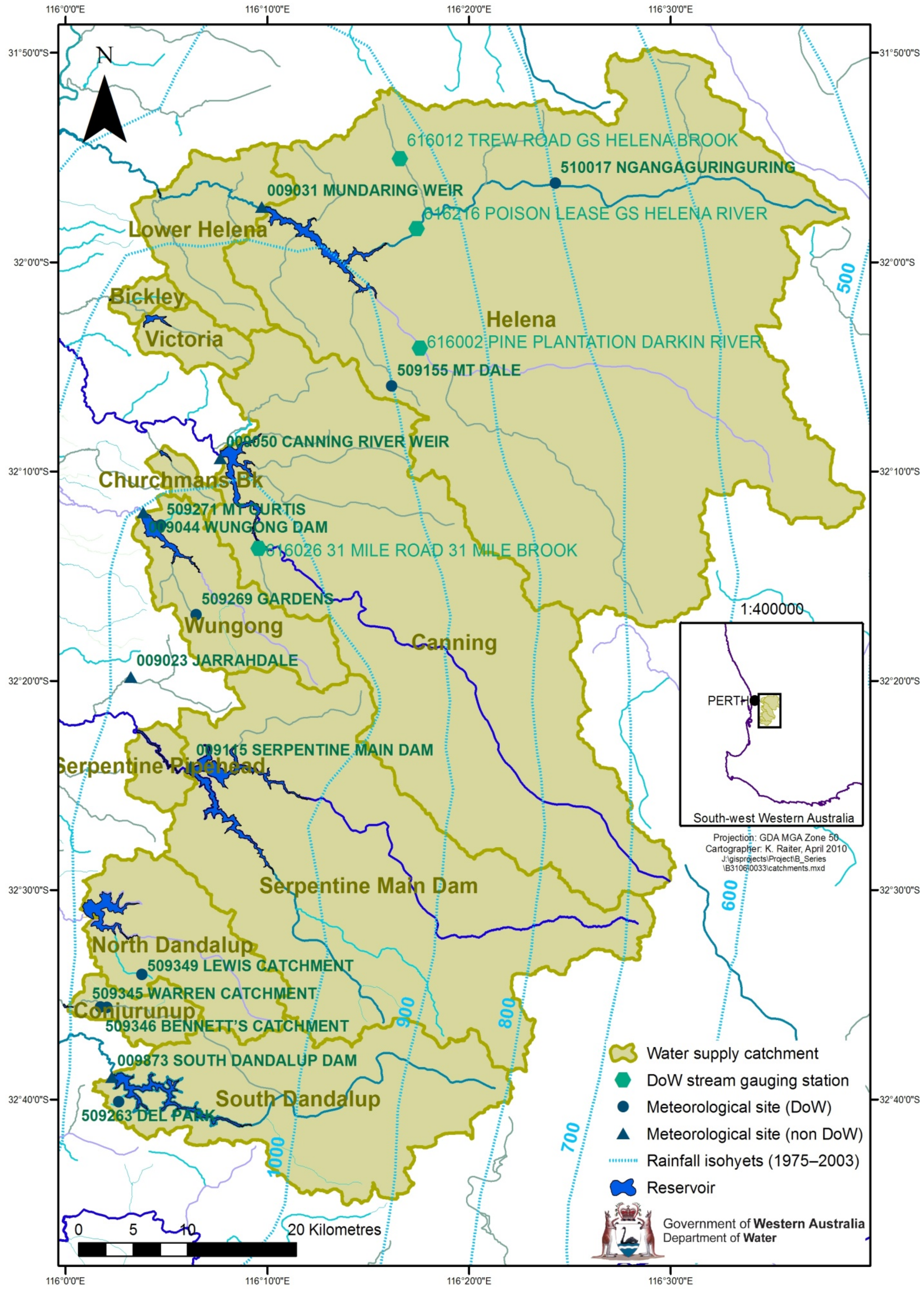

Figure 1 The Darling Range water supply catchments

Nicholls et al. (1999) concluded that the decline in rainfall has been accompanied by a decline in the amount of rain falling in extreme rainfall events.

A step-decline in streamflow accompanied the drop in rainfall, with streamflow decreasing by around three times the decrease observed in rainfall (Rogers & Ruprecht 1999; IOCI 2002; Durrant 2009).

The period since 2001 has been even drier than the preceding years. This concurs with projected climate trends (CSIRO 2009), although statistical tests have failed to identify a statistically significant declining trend in rainfall (Durrant 2009; Petrone et al. 2010). A longer period is required to ascertain whether the trend observed in the period 2001–08 is due to climate variability alone or represents a shift in the climate.

Catchment areas and yields

The areas and streamflows of the water supply catchments are shown in Figure 2. The Helena River catchment has the largest area but on average produced only 16 GL of flow, largely because the majority of its catchment extends east into lower rainfall areas. The Serpentine and Canning catchments produced the greatest reservoir inflows (33 and 25 GL respectively). The total annual flow into all the reservoirs was 110 GL in 2007 and averaged 152 GL over the period 1975–2008.

Durrant (2009) observed a decrease in streamflow in the majority of sites analysed across the south-west of Western Australia, together with a shift in the peak flow month, with peak flows occurring about one month later in the ‘1997 to current’ period compared with the 1975–96 period.

For some of these streams, Durrant (2009) found that there had been a second step-change in streamflow further to the step-change observed in 1975, although this second change has not been observed consistently across the region (Durrant 2009). At the Helena River Poison Lease gauging station, Durrant found a decreasing trend in annual flows since 1975, but this trend was not significant; that is, it could be attributed to natural streamflow variability.

Climate variability can mistakenly be attributed to climate change in some cases, as well as obscuring underlying trends in other cases (Durrant 2009).

The South-West Sustainable Yields project predicts a decrease in rainfall and runoff by an average of 8 and 25% respectively, and an increase in runoff variability relative to 1975–2007 by around 2030 (CSIRO 2009).

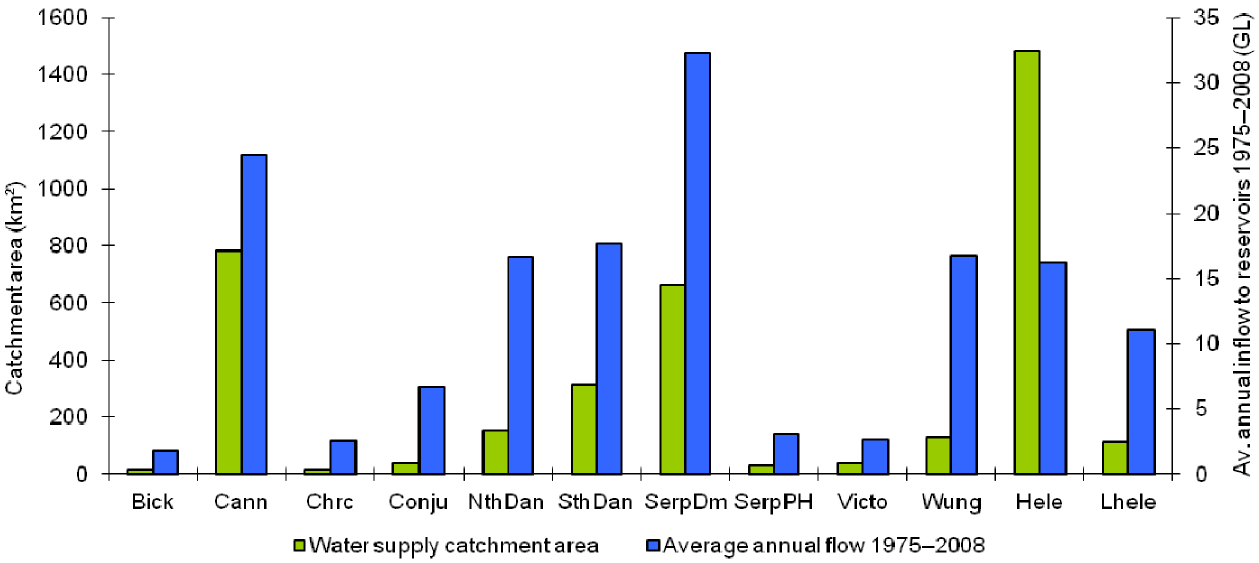

Figure 2 Catchment areas and average flows of the Darling Range water supply catchments

Geology and hydrology

The Darling Range water supply catchments are located on the western edge of the Archaean Yilgarn plateau and comprise major valleys, lateritic uplands, and minor valleys within the upland areas (Mauger et al. 1998). The bedrock consists mainly of granite and gneisses with doleritic intrusions (Mauger et al. 1998).

Above the bedrock, and weathered from it, lies a layer of kaolinitic sandy clay which acts as the lateral conducting layer for deep groundwater (Peck et al. 1980; Mauger et al. 1998). This is overlain by a thick, clayey pallid zone, a mottled zone, and a lateritic duricrust. Root channels dissect the soil profile and are important in groundwater recharge.

Topsoils are generally highly permeable and include red, yellow, and brown soils; loams, gravels, sands and clays interspersed by lateritic duricrust and igneous rocky outcrops (Mauger et al. 1998; CSIRO 2009).

The deeply weathered lateritic profiles are relatively permeable and provide a large soil water store that is available to deep-rooted vegetation (to 40 m depth) year-round. This leads to sluggish streamflow responses to rainfall and low catchment water yields (Mauger et al. 1998; Ruprecht & Pearcey 1999; CSIRO 2009).

Shallow throughflow, also called subsurface flow or interflow, is considered the dominant source of streamflow, occurring through the formation of a temporary perched aquifer above a relatively impermeable duricrust or clay horizon in winter (Ruprecht & Pearcey 1999). Saturation excess, also called direct runoff, dominates instantaneous flood peaks resulting from intense rain falling on saturated land. Saturation excess occurs more regularly where the groundwater is at or near ground level.

Groundwater discharge occurs primarily in the western margins of the catchments and is generally considered a relatively minor component of surface water yields in forested catchments (Ruprecht & Pearcey 1999; Mauger et al. 1998), though groundwater levels affect other runoff-generation mechanisms such as throughflow (Ruprecht & Schofield 1989). Recent work has shown that streamflows are strongly correlated with groundwater levels, and that groundwater may play a dominant role in streamflow generation, either directly or indirectly via enhancing saturation excess and shallow throughflow (Hughes et al. 2012).

Groundwater levels have generally declined since 1975, particularly in the last decade, due an emerging deficit between rainfall which has declined and evapotranspiration which has not declined to the same extent (Croton & Reed 2007; Reed 2008; Croton & Dalton 2011; CSIRO 2009; Hughes et al. 2012). In fact, in many areas evaporation has increased with vigorous growth and high leaf and sapwood areas in regrowth forests (Croton & Reed 2007; Macfarlane et al. 2010; Silberstein et al. 2011; Croton & Dalton 2011). Silberstein et al. (2011) suggest that approximately one third of the runoff decline in the study area is due to changes in forest structure that have taken place since European colonisation. These trends have resulted in less groundwater recharge (less rain and a greater proportion used by vegetation) and, in some areas, more net uptake of groundwater and/or soil moisture by deep-rooted vegetation.

Where groundwater levels decline to the extent that they disconnect from stream zones, the streamflow may decrease in three ways: 1) throughflow, which may be strongly influenced by groundwater and soil moisture levels, declines; 2) saturated areas – which would otherwise produce direct overland flow – contract; and 3) groundwater no longer discharges into streams; instead some flow may actually be lost from the stream to the surrounding soil matrix (Reed 2008; Silberstein et al. 2011; Hughes et al. 2012). In some cases, perennial streams have become ephemeral (Barrett 2008), with consequences for stream-dependent flora and fauna.

Vegetation, land use, and mining

The catchments fall within the Northern Jarrah Forest biogeographic subregion (McKenzie et al. 2002). The catchments are largely covered by native vegetation within state forests, national parks and other conservation areas, although small areas of freehold land have been cleared for agriculture. Forest structure is variable, ranging from old growth stands to pole and sapling stands.

State forests are managed for multiple uses: timber, conservation, recreation, water production, and bauxite mining. State forest land is vested in the Conservation Commission and managed by the Department of Environment and Conservation under the Forest Management Plan. The catchments produce high quality drinking water.

Special mining leases under various state agreement acts exist over much of the Crown land in the catchments, enabling mining companies to extract bauxite from the alumina-rich mottled zone. The lease obliges miners to protect environmental values and rehabilitate mine sites. Prior to 1988, mined areas were rehabilitated with pines and eastern Australian tree species. Since 1988, mined areas have been rehabilitated with native species. Current rehabilitation practices generally result in high species recovery and dense vegetation cover that can reduce streamflows (Croton et al. 2005). Macfarlane et al. (2010) demonstrated that the water use of regrowth forests can be more than double that of old forests.

2 Methods

2.1 Factors investigated

This report tests the hypothesis that below-average runoff in 2007 can be attributed to:

- Changes in rainfall-runoff relationships under recent dry conditions
- Changes in rainfall intensity and temporal distribution
- The lag effect of the previous year's very low rainfall (and hysteresis in the system)
- Rainfall seasonality and dry mid-winter periods.

This report does not directly investigate changes in vegetation cover and temperature which may also have contributed to the below-average runoff observed in 2007. While this report does not examine groundwater trends directly, it does consider the strong influence of groundwater levels and soil moisture on runoff.

2.2 Data

The Department of Water's Hydstra database supplied the daily and hourly rainfall data, and gauged streamflow data. The Water Corporation supplied estimates of monthly inflow into the water supply reservoirs, and monthly rainfall data for seven nearby meteorological stations. The bore data in Appendix A was supplied by the Water Corporation and Alcoa.

Wet season rainfall was calculated as the sum of the rain from May to October, in line with the Indian Ocean Climate Initiative (Nicholls et al. 1999; IOCI 2002). Summer rainfall was excluded as it rarely contributes to runoff (Jeevaraj pers. comm.). Wet season rainfall was compared to runoff over the whole 'water year', defined as May to April, in line with analyses made by IOCI, the Water Corporation, and CSIRO (Nicholls et al. 1999; IOCI 2002; Li et al. 2005; Water Corporation 2008b).

A 'recent climate' comparison period was included to compare rainfall and runoff variables for the longer 1975–2008 period with data from 2001 to 2008. This was based on the most recent Water Corporation climate period for the IWSS, and the findings of Durrant (2009) that more significant step declines happened during 2000–01 than for all other years after 1975.

Relationships between rainfall and runoff were investigated using linear, polynomial trend lines and tanh curves, as described by Grayson et al. (1996).

Meteorological stations used for analysis of daily rainfall were selected according to their locations and the range and quality of their data records (Table 1). Missing daily data for Jarrahdale were filled using interpolated SILO data. For other stations, years of hourly data with more than 10% missing data, and years of daily data with more than 4 days missing were excluded.

Histograms of daily rainfall for the meteorological stations were visually assessed for dry periods and observable differences in rainfall patterns between years with similar rainfall.

Catchment areas were calculated from hydrographic catchment boundaries generated by analysis of a digital elevation model, supplied by Geographic Information Analysis Pty Ltd.

Table 1 Meteorological stations used in rainfall analysis

BoM ref.	Name	BoM context	Easting	Northing	Rainfall zone	Owner	Data
009023	Jarrahdale	Jarrahdale	410956	6422525	1000–1050	BoM	d
009031	Mundaring	Mundaring Weir	420798	6464123	850–900	BoM	d
009115	Serpentine	Serpentine main dam	415661	6414663	1000–1050	BoM	d
509155	Mt Dale	Little Darkin River	431042	6448418	900	DoW	d + h
509263	Del Park	South Dandalup trib.	410332	6385039	1050	DoW	d + h
509269	Gardens	Seldom Seen Creek	415970	6428114	1000–1050	DoW	d + h
509271	Wungong Dam	Waterfall Gully	413169	6435979	1000–1050	DoW	d + h
509345	Warren	Little Dandalup trib.	408839	6393384	1000–1000	DoW	d + h
509346	Bennett’s	Little Dandalup	409359	6393359	1000–1050	DoW	d + h
509349	Lewis	North Dandalup	412034	6396289	1050	DoW	d + h
510017	Helena River	Ngangaguringuring	443715	6466411	700	DoW	d + h

BoM = Bureau of Meteorology
DoW = Department of Water
d = daily
h = hourly

Runoff data were tested for autocorrelation using the autocorrelation and rank-sum test in the TREND trend and change detection software (Chiew & Siriwardena 2005). In all but one case the results from the two tests were identical. For brevity, only the autocorrelation test results are presented here.

3 Results

The average wet season rainfall for the metropolitan water supply catchments in the south-west of Western Australia over the period 1975–2008 was 874 mm, measured at Jarrahdale[4] (Fig. 3). The average annual streamflow for this period was 152 GL. In 2007, wet season rainfall of 998 mm exceeded this average by 14%, but the 109 GL of runoff from the Darling Range water supply catchments was 28% short of the average, relative to 1975–2008 records.

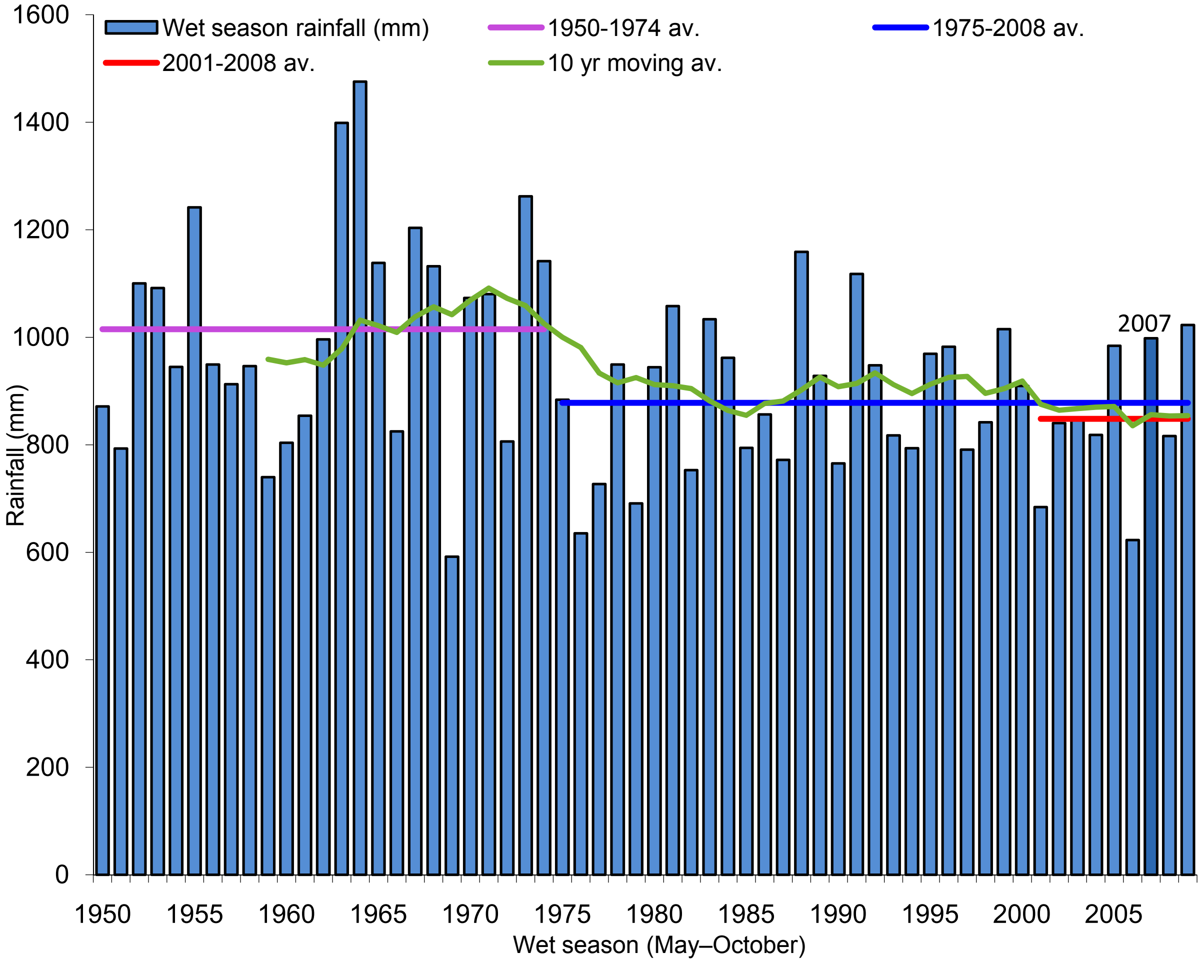

Figure 3 Rainfall decline at Jarrahdale

3.1 Recent dry conditions

This section tests the hypothesis that the low runoff observed in 2007 is a product of the relatively dry period experienced since 2001.

---

[4] considered representative of the Darling Range water supply catchments (Jeevaraj, pers. comm.).

Figure 4 shows the runoff coefficients for all the catchments for the last 60 years. In all catchments, the runoff coefficients during 2007 were similar to 2001–09 averages. This supports the hypothesis stated above.

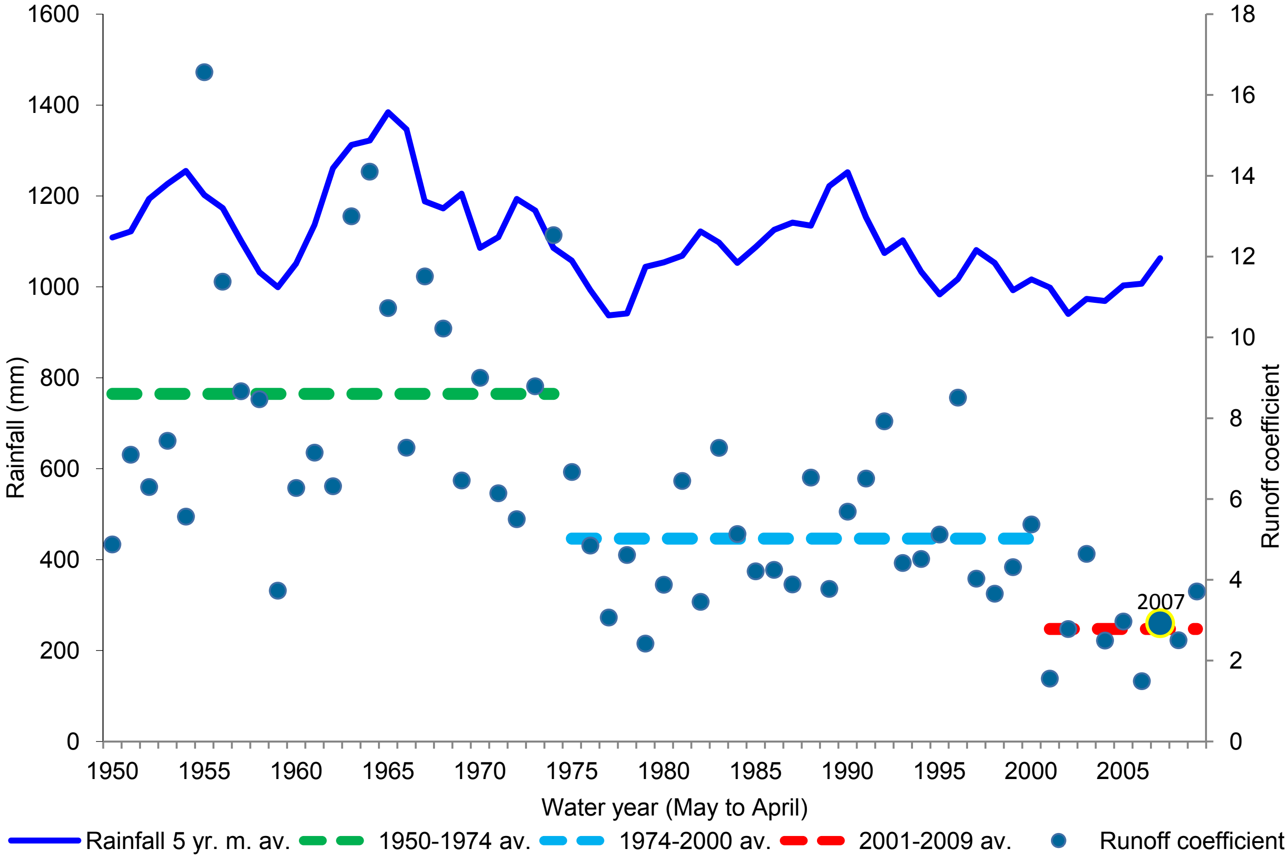

Figure 4 Darling Range runoff coefficients

Figure 5 shows the percentage of rainfall that flowed into the reservoir for each of the water supply catchments, based on nearby rain gauges (Table 1). Runoff coefficients in the Darling Range have declined over recent decades, with those observed during 2001–09 being 32–47% lower than those during 1975–2000. Runoff coefficients for 1975–2000 were 16–52% lower than those for 1950–74.

The recent extended period of below-average rainfall has exacerbated declining groundwater levels and reduced groundwater–surface water connectivity in many areas (Reed 2008; Appendix A), and is likely to have caused lower soil moisture levels.

These factors have effectively increased the amount of rain required to generate streamflow (Silberstein, pers. comm. 22.09.2009). Figure 6 further illustrates the change in the rainfall-runoff relationships between the 1950–74; 1975–2000; and 2001–08 periods. Note that polynomial curves were selected to represent the rainfall-runoff relationship for the periods 1950–74 and 1975–2000, as they reflected the curved shape of the data, and had the greatest fit. A linear trend was selected for the period 2001–08, as it had the greatest fit in this case – this may be due to there being insufficient data points to reveal a curved relationship. See Appendix B for the data.

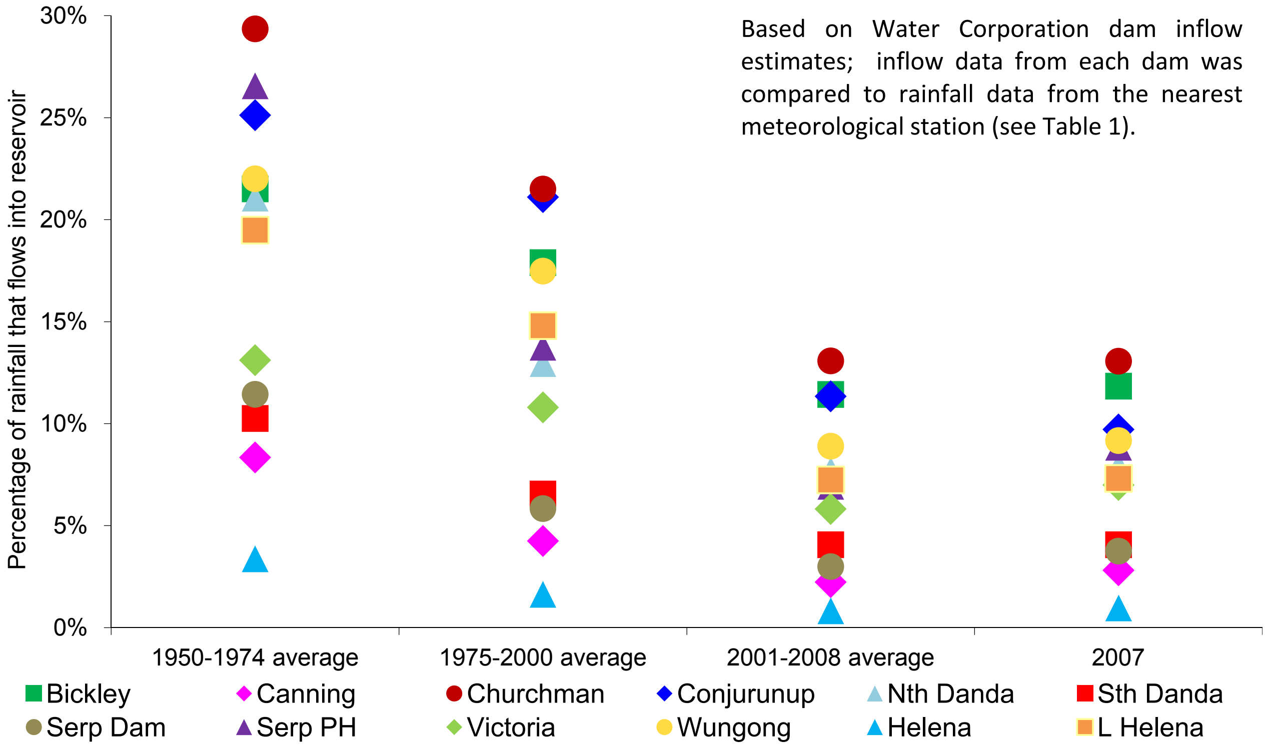

Figure 5 Runoff coefficients in the water supply catchments over different periods

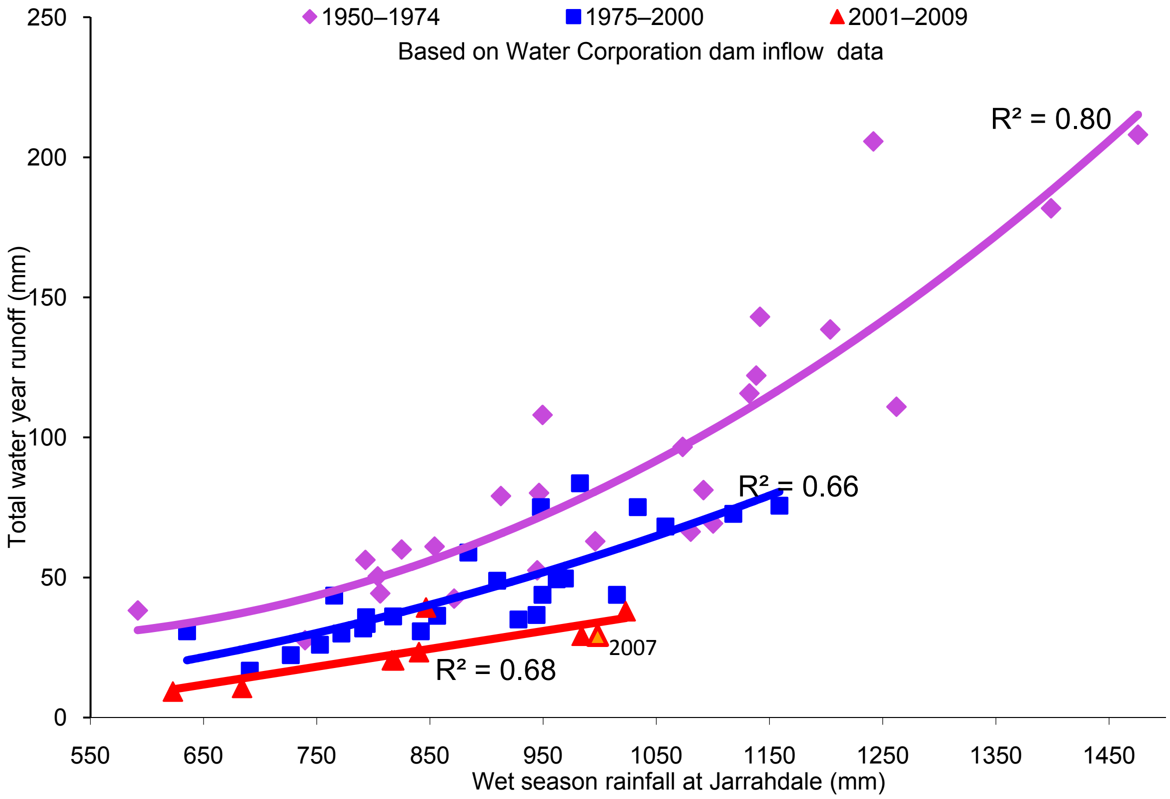

Figure 6 Changing rainfall-runoff[5] relationships in Darling Range catchments

---

[5] Runoff, expressed in mm, is calculated by dividing catchment discharge by total catchment area (km²).

3.2 Changes in temporal rainfall distribution

This analysis tests the hypothesis that rainfall was less intense but of longer duration in 2007 than in the average of the 1975–2008 period. The hypothesis is tested on both hourly and daily scales.

If rainfall in 2007 was less intense but of greater duration, the proportion of water lost from the catchments to interception, evaporation and transpiration would be greater (Schofield 1984), thus decreasing the proportion of water reaching streams. Schofield (1984) showed that interception loss, as a percentage of total rainfall, was strongly dependent on the amount of rainfall up to 10 mm, and was highest in rain periods with a total of less than 5 mm. In rain periods above 10 mm, interception loss remained relatively constant. A decrease in intensity would also reduce the streamflow generated by saturation excess, a mechanism dependent on intense rain events (Ruprecht & Pearcey 1999).

The specific variables examined included rain hours and rain days, mean rainfall per rain hour/rain day, numbers of high (≥ 10 mm), very high (≥ 20 mm), low (≤ 5 mm) and very low (≤ 2 mm) rain hours/rain days, as well as the proportion of rain received in those rain days/rain hours. Averages of the 2001–08 period are included for comparison.

3.2.1 Differences in hourly rainfall

At the hourly scale and for all sites, rainfall during the 2007 wet season was less intense and spread over more time than the 1975–2008 average.

The proportion of rain with intensity greater than or equal to 10 mm/h in 2007 was about half of the 1975–2008 average at seven of eight sites (Fig. 7)[6]. One site received no rainfall at greater than 10 mm intensities in 2007.

The relative absence of rain at ≥ 10 mm/h in 2007 relative to both of the comparison periods implies that less rain fell in conditions conducive to forming a temporary perched aquifer and developing shallow throughflow, or saturation-excess runoff.

Conversely, the higher proportion of rain in 2007 that fell in low-intensity events (≤ 5 mm; Fig. 8) implies that more rain would have been lost through interception and evaporation from soil surfaces. Of the water that percolated into the soil, a higher proportion would have been taken up by plants before it could flow into streams or recharge the groundwater.

---

[6] Note: ‘Av.’ denotes the average of the eleven sites; sites are arranged in order from north to south – the three left-most stations in each graph are in areas with lower average rainfall.

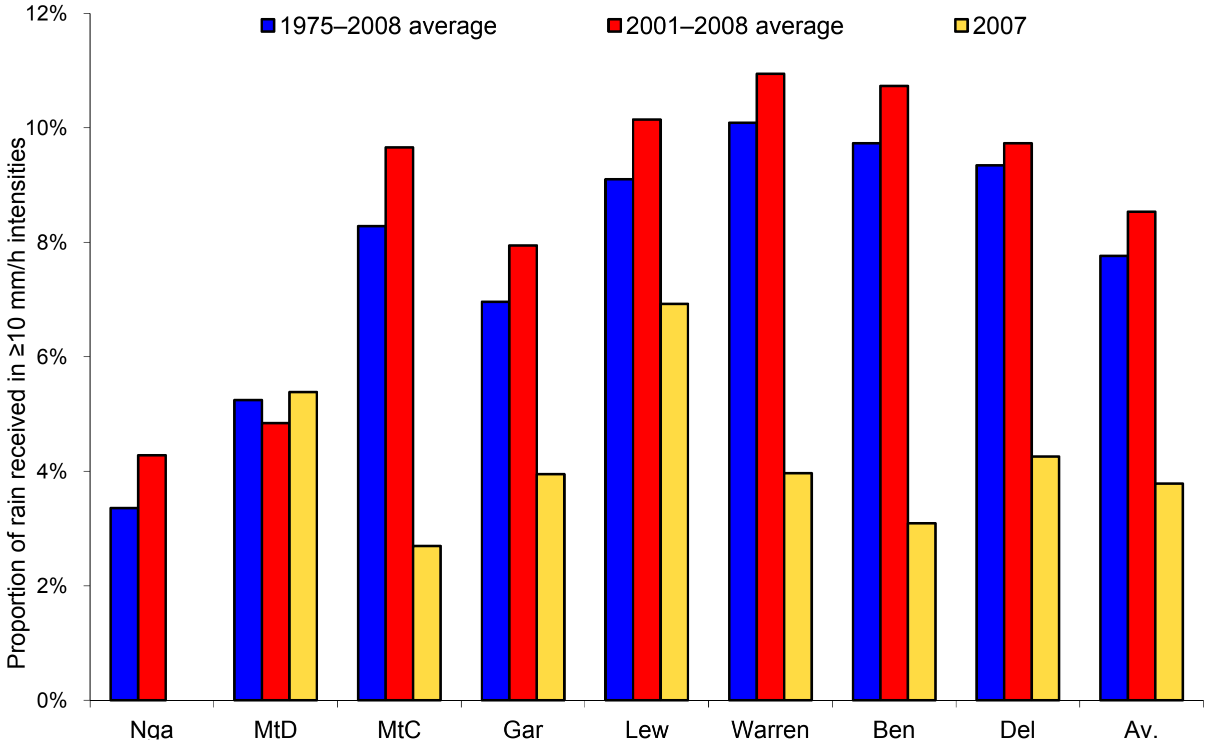

Figure 7 Proportion of ≥ 10 mm/h rainfall

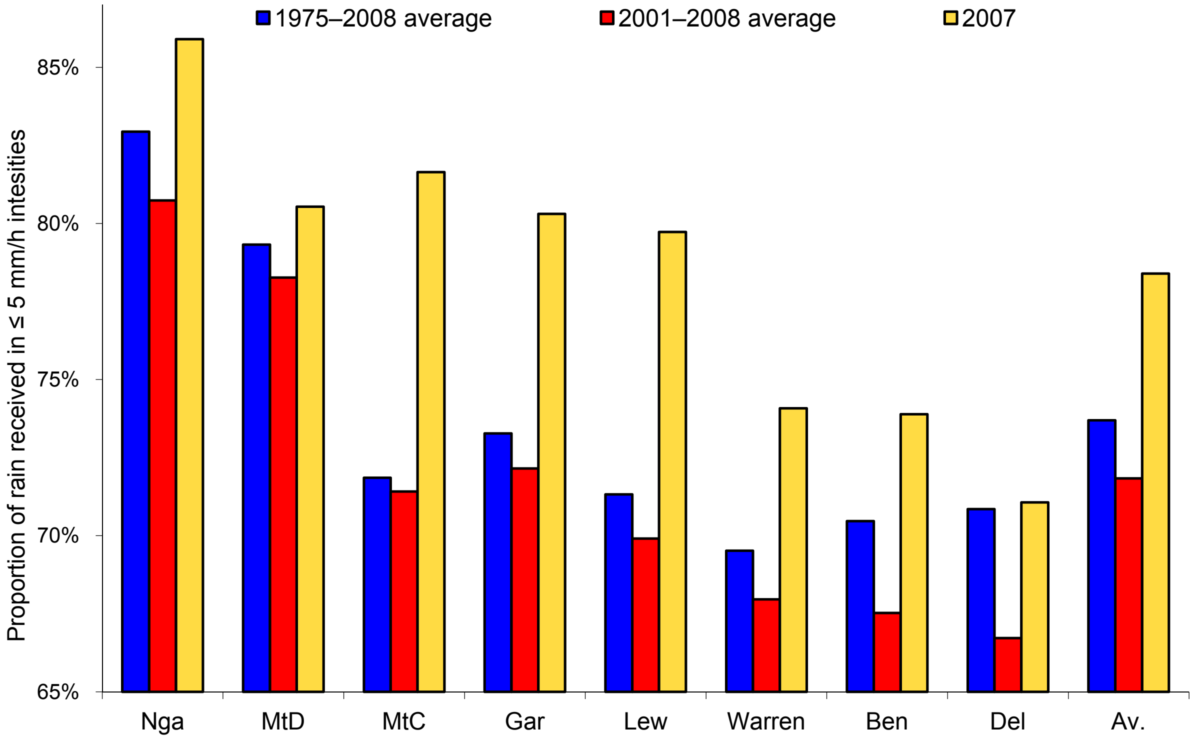

Figure 8 Proportion of ≤ 5 mm/h rainfall

At all sites, rain fell over more hours during the 2007 wet season than during an average 1975–2008 wet season (Fig. 9). In contrast, the average number of rain hours per wet season in the 2001–08 period was lower than in the 1975–2008 average.

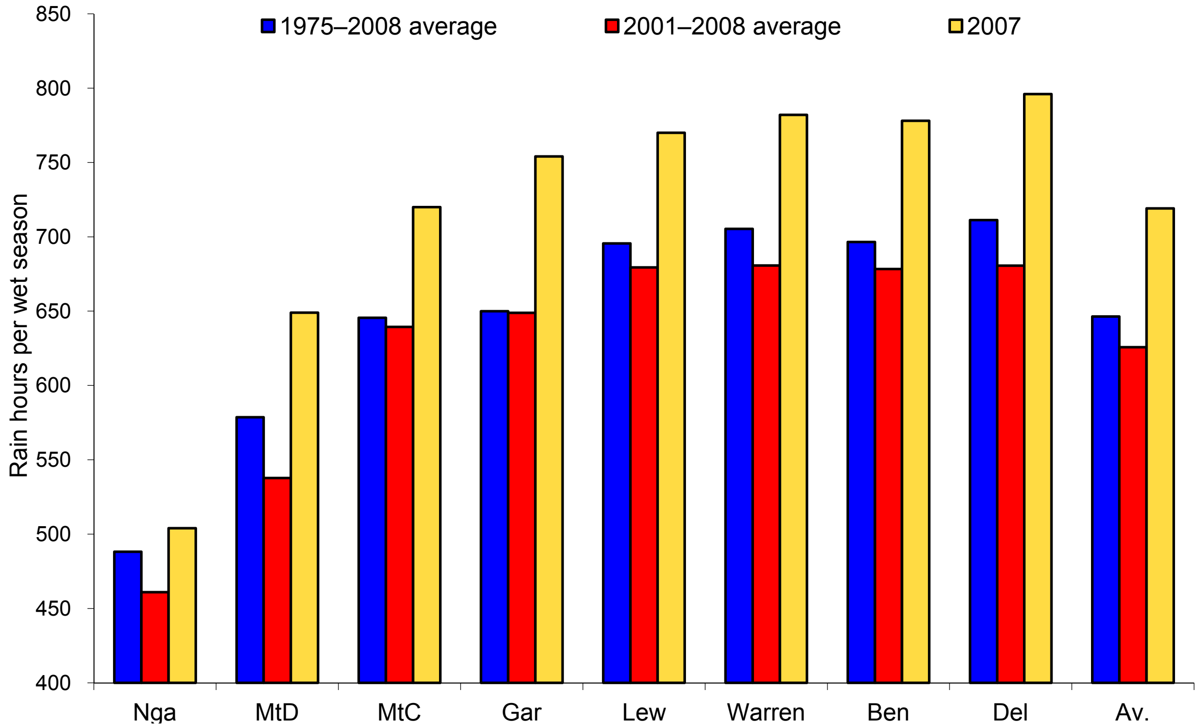

Figure 9 Hours of rain during the wet season

This implies that rain drops sat in canopies and other vegetation surfaces, exposed to wind and sunshine and the evaporative demand of the atmosphere for more hours in 2007 than the average for the 1975–2008 period. Similarly, water would have sat on or near the soil surface for more hours in 2007, prone for a greater length of time to evaporation or uptake by shallow-rooted plants. A smaller proportion would have remained for generating streamflow.

The mean rainfall per rain hour was generally lower in 2007 than in 1975–2008 or 2001–08 (Fig. 10).

The differences between the 2007 data and the 1975–2008 averages contrasted with the post-2001 trend. While the 2001–08 period had, on average, less low intensity rainfall, more high intensity rainfall, and fewer rain hours, in 2007 rain fell over more rain hours and at lower intensities. A clear post-2001 trend was not visible in the mean rainfall per rain hour, although mean rainfall per rain hour was generally lower in the 2007 than the 1975–2008 records.

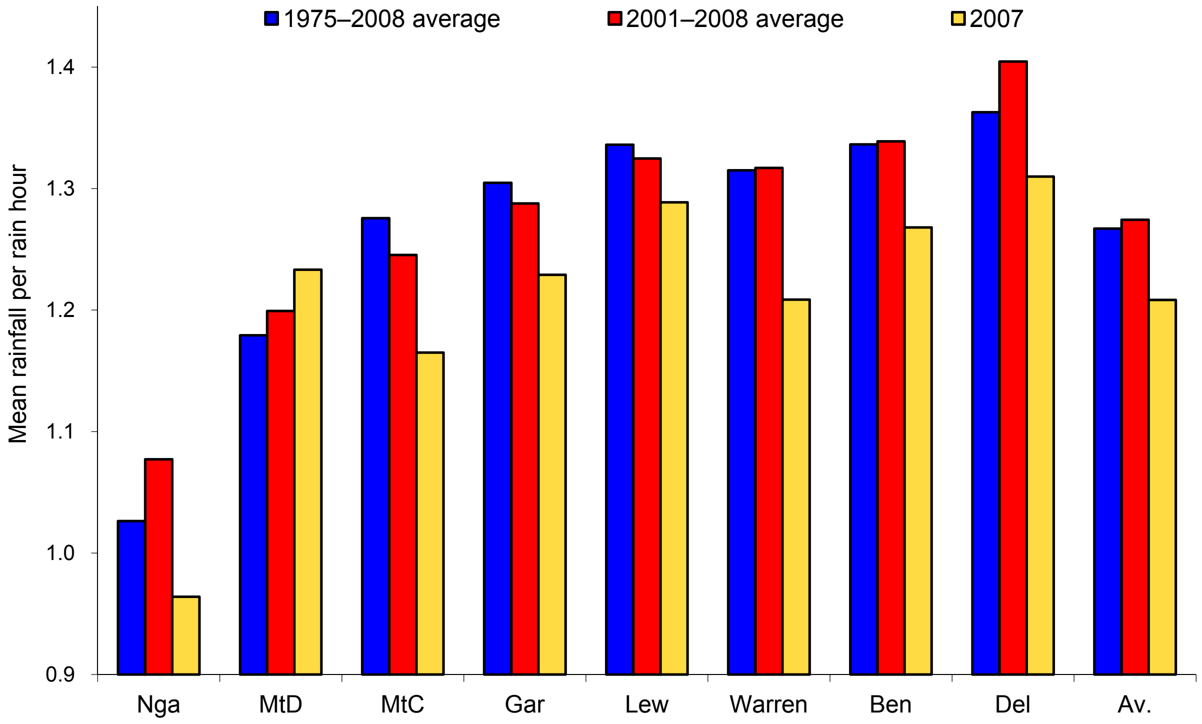

Figure 10 Mean rainfall per rain hour at eight Darling Range locations

Overall, the results for the hourly data analyses support the hypothesis of less intense, longer duration rainfall. It was not possible in this analysis to quantify the effect that this would have had on runoff – this would require further analysis of temporal rainfall distribution patterns (such as duration of rainfall events, length of dry periods, intricate modelling of streamflow generation responses to rainfall intensities, and an improved understanding of vegetation interception capacities.

3.2.2 Differences in daily rainfall

The rainfall during May–October was, in almost all cases, spread over more rain days in 2007 than in 1975–2008 (Fig. 11). At all sites, there were more rain days in the 2007 wet season than in the 2001–08 average wet season.

The trend of less intense rainfall distributed over more time apparent at the hourly scale is not apparent at the daily scale for low and high rainfall events. At most sites, there were more days in 2007 with ≥ 10 mm of rain than the average for the 1975–2008 period (Fig. 12). The 2001–08 period average was characterised by both fewer rain days per wet season and fewer days with ≥ 10 mm rain.

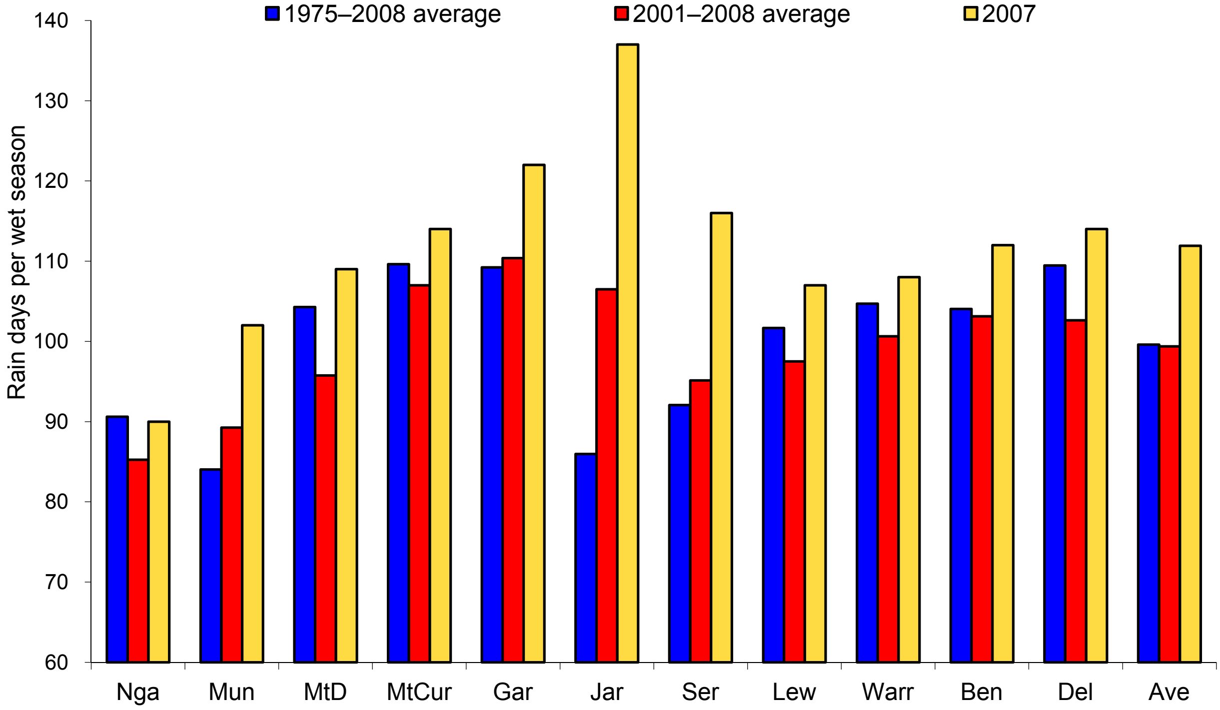

Figure 11 Wet season rain days for 1975–2008, 2001–2008, and 2007

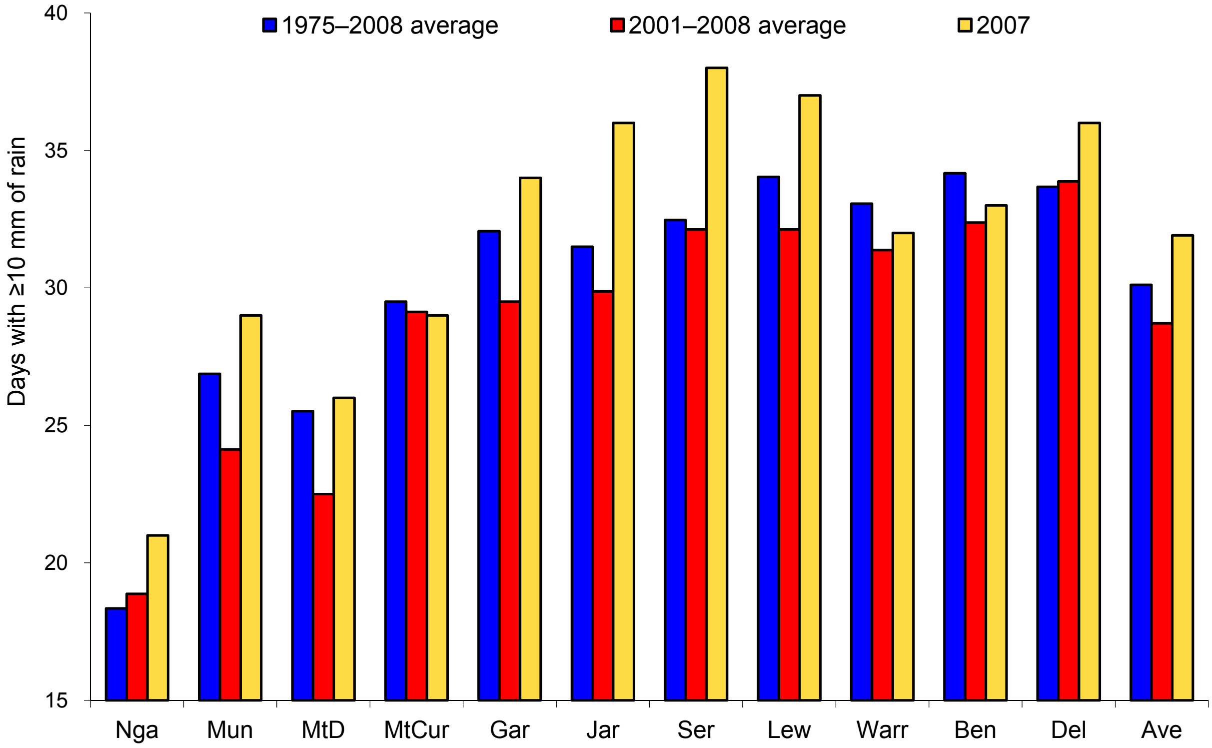

Figure 12 Days with ≥ 10 mm of rain during the wet season

In contrast to the hourly rainfall intensity analyses, the results for the daily data analyses do not support the hypothesis of less intense, longer duration rainfall. While there were more wet season rain days in 2007 than in the average 1975–2008 wet season, there were also more days with 10 mm or more of rain.

3.3 Hysteresis

This section examines the hypothesis that the lower-than-average runoff in 2007 can partly be accounted for by the preceding very dry year – 2006 – by testing for autocorrelation in runoff.

Hysteresis refers to the lagging of an effect behind its cause, by which the state of a system (e.g. runoff) depends not only on the present stimulus (current year rainfall), but also on the previous state of the system (previous year's runoff). TREND tests for autocorrelation in dam inflow data indicated that hysteresis exists in all of the catchments at 0.01 or 0.05 significance levels (shown in Appendix B). This is in accordance with the findings of Petrone et al. (2010), and Water Corporation models, which factor a lag-1 correlation into runoff projections (Jeevaraj, pers. comm.).

With only 798 mm recorded at Jarrahdale over the whole water year, 2006 was one of the driest years on record compared with the average of 1049 mm[7] and would have left the catchments drier (both in terms of soil moisture and groundwater storage) than average, and these drier antecedent conditions would have affected the process and timing of runoff. Notably, February 2007 was the first month in the recorded history of the IWSS with no streamflow into the reservoirs.

The drier-than-normal antecedent conditions are evident in the slow development of the streamflow in the water supply catchments for January to June of 2007, relative to recent averages. This was the case despite the wet season in 2007 not having an appreciably late start, with higher than average rainfall in April (Section 3.4).

Significant streamflows in the IWSS generally develop between April and June. In 2007, however, it was not until July (a particularly wet month; Fig. 14) that the catchments were wet enough for considerable streamflows to occur and even then they only just exceeded the 2001–08 average, and remained well below the 1975–2008 average. Figure 13 shows how monthly streamflows in 2007 varied from period averages, with particularly low flows in the first half of the year, indicating that the antecedent conditions remaining from the previous year were not conducible to flow.

Groundwater trend observations support these findings: in some parts of the Cobiac catchment, groundwater levels did not appear to recover at all following the dry 2006 winter. In fact, 'it appears that the "trough" following the 2005 summer becomes the "peak" following the 2006 winter, indicating that in some areas, there was no groundwater recharge during that season' (Reed 2008), and all the water that infiltrated just replaced soil water storage.

---

[7] For the 1975–2007 period

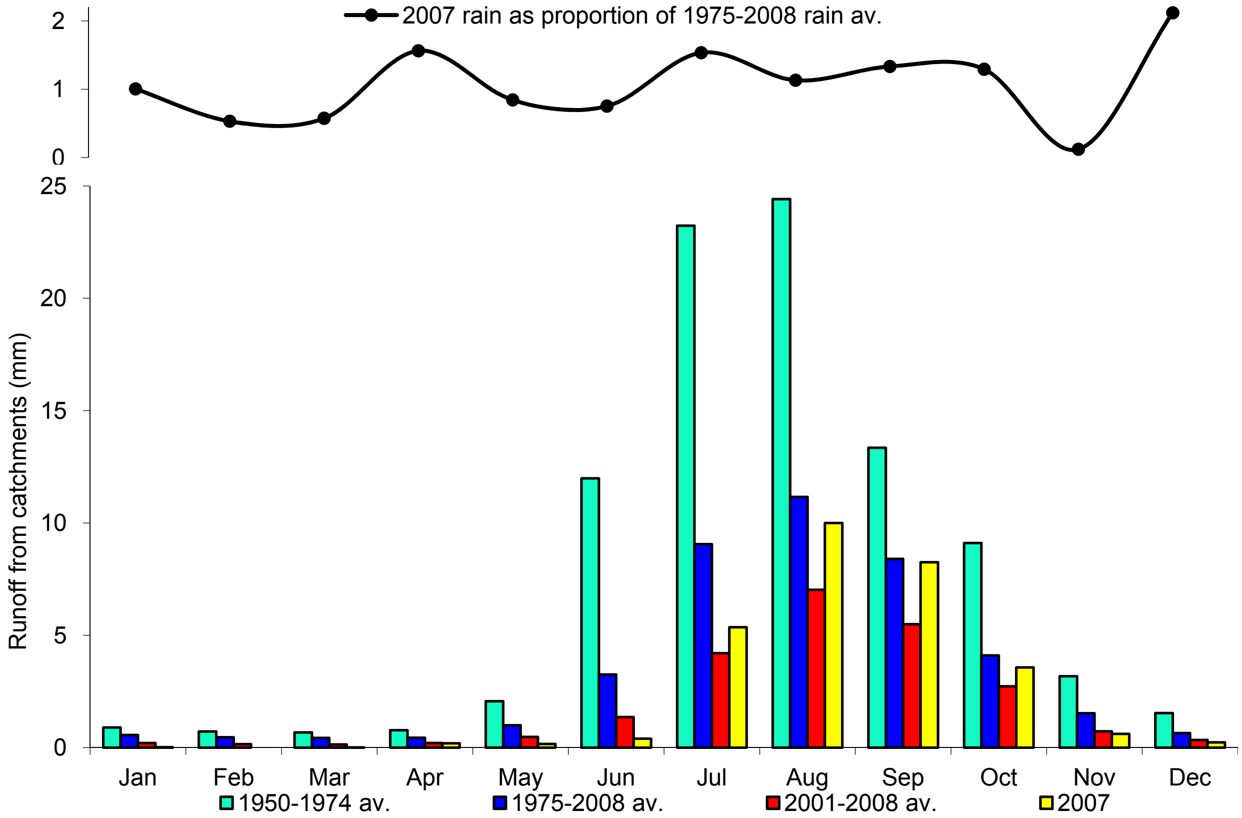

Figure 13 Average monthly streamflow in the northern IWSS catchments

3.4 Seasonality of flow and dry periods

This section examines the hypotheses that the lower-than-average runoff in 2007 can partly be accounted for by: 1) a late start to the wet season, or 2) dry mid-winter periods.

Autumn rains, which wet catchments and prepare them for winter runoff, have declined in frequency more than other weather patterns (IOCI 2002). This trend may play a role in the disproportionate decline in runoff relative to rainfall.

An exceptionally late season start in 2007 could be expected to have led to even drier catchment conditions than average at the beginning of the wet season, resulting in more rainfall required to generate streamflow. Similarly, dry periods in the middle of the wet season may be expected to lead to a mid-winter drying out of the catchments, with the rainfall following the dry period being 'used up' in rewetting the catchment rather than contributing to streamflow.

3.4.1 Seasonality and rain required to generate streamflow

Figure 14 shows monthly rainfall at Jarrahdale in 2007 and averaged for recent periods.

The peak rainfall month in 2007 was July, consistent with the patterns of both 1975–2008 and 2001–08 periods. April rains in 2007 were above average, while May and June 2007 rainfalls fell below the recent period averages. July 2007 rainfall was well above all the period averages assessed, and late winter (August, September, October) rainfall also exceeded these averages. There was no noticeable 'late start' to the wet season in 2007. The first hypothesis – that lower-than-average runoff in 2007 can partly be accounted for by a late start to the wet season – is not supported in this instance.

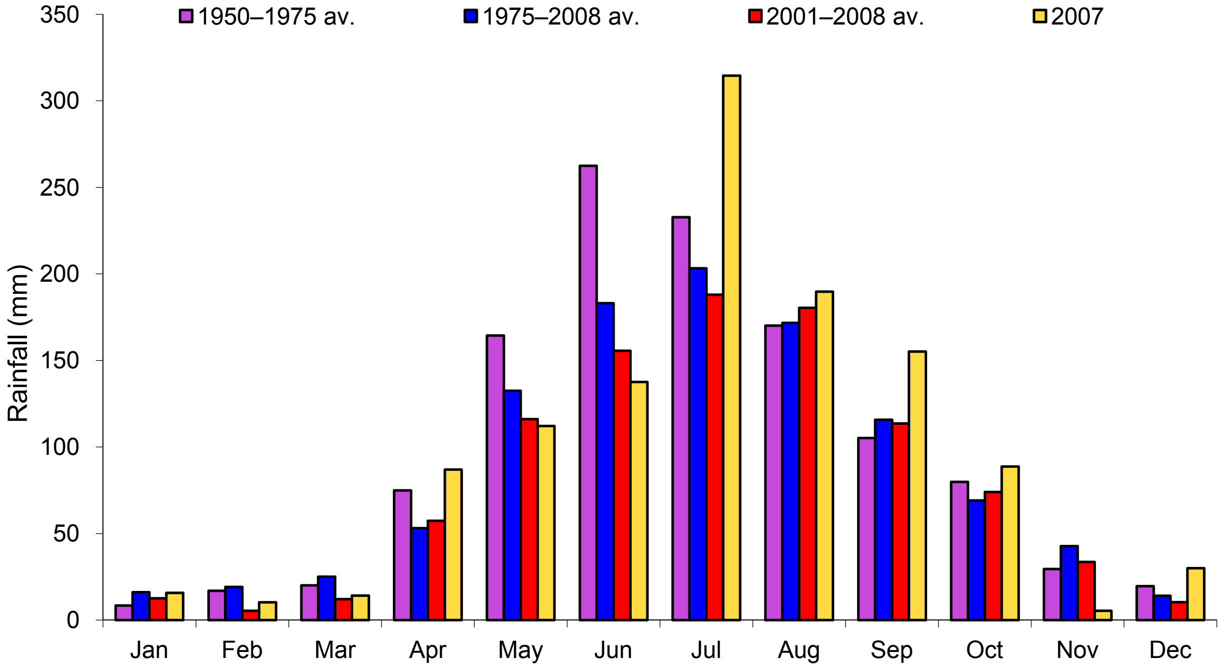

Figure 14 Average monthly rainfall at Jarrahdale

Silberstein (pers. comm. 22.09.2009) observed that, in recent years, more rain is required to generate streamflow than previously. This probably applies more to streams in the western parts of the surface water catchments where some groundwater-surfacewater connectivity exists. In these areas, where groundwater levels have declined, the rain required to create saturated areas and 'wet' catchments before surface water flows are generated is greater. Where groundwater is permanently disconnected from stream zones, groundwater decline is unlikely to affect the rainfall required to initiate streamflow (Appendix C).

Analysis of the rain needed to generate streamflow in wetter parts of the catchments where groundwater–stream zone connectivity exists would require further analysis and/or modelling to separate baseflow from streamflow and is beyond the scope of this report.

3.4.2 Dry mid-winter periods

Weekly rainfall totals for two years (1996 and 1999) with rainfall similar to 2007 but considerably higher streamflows were compared with those in 2007. This was done to identify any dry mid-winter periods that could have led to catchments drying out during the wet season and requiring more rain to be 'rewetted', thus leading to low rainfall coefficients. This analysis did not reveal any more or longer dry mid-winter patches in 2007 compared to the comparison years (Appendix D). The hypothesis of mid-winter dry patches contributing to the low runoff coefficient in 2007 is thus rejected.

4 Discussion

This report provides a qualitative assessment of some factors that may have contributed to low runoff coefficients in 2007 relative to the post-1975 period.

The recent decadal decline in runoff coefficients in the water supply catchments is the strongest explanation for the low runoff in 2007. The similar rainfall and runoff observed in 2005 provide an excellent example of this.

This decline in runoff coefficients is likely associated with a deficit between groundwater recharge from rain and groundwater uptake by vegetation that emerged following the rainfall decline in the mid 1970s, but has been exacerbated in the recent dry decade. This deficit has led to drops in groundwater levels, particularly in recent drought years, resulting in loss of groundwater–surface water connectivity and reduced groundwater discharge, saturated overland flow, and throughflow.

A lower percentage of intense (≥ 10 mm/h) rain, a higher proportion of lower intensity (≤ 5 mm/h) rain and rainfall being spread out over longer time periods may have also reduced runoff coefficients in 2007. These factors would increase the proportion of rainfall lost through interception and evapotranspiration and reduce throughflow and saturation-excess runoff generation processes.

Daily rainfall trends in the south-west have been studied extensively (Hennessey et al. 1999; Li et al. 2005; CSIRO 2007), but hourly rainfall trends have not. This report has found a number of noteworthy differences in hourly rainfall patterns between the 1975–2008 and 2001–08 periods, and 2007. Some of these indicate clear trends, where the daily data are inconclusive; some of these contradict the trends observed on the daily scale.

Temporal rainfall patterns in 2007, for the most part, contrasted with the trend observed in the recent, dry period post-2001. The period 2001–08 had fewer rain hours, more high intensity and less low intensity rainfall than the 1975–2008 average. Both the decline in the number of rain days and the decline in the amount of rain falling in high rainfall events are in agreement with the decline noted by Nicholls et al. (1999).

The lag effect of the dry previous year probably also had an effect on runoff in 2007, with hysteresis an observed attribute of the catchments.

Figure 15 suggests a possible representation of the factors involved in declining runoff coefficients.

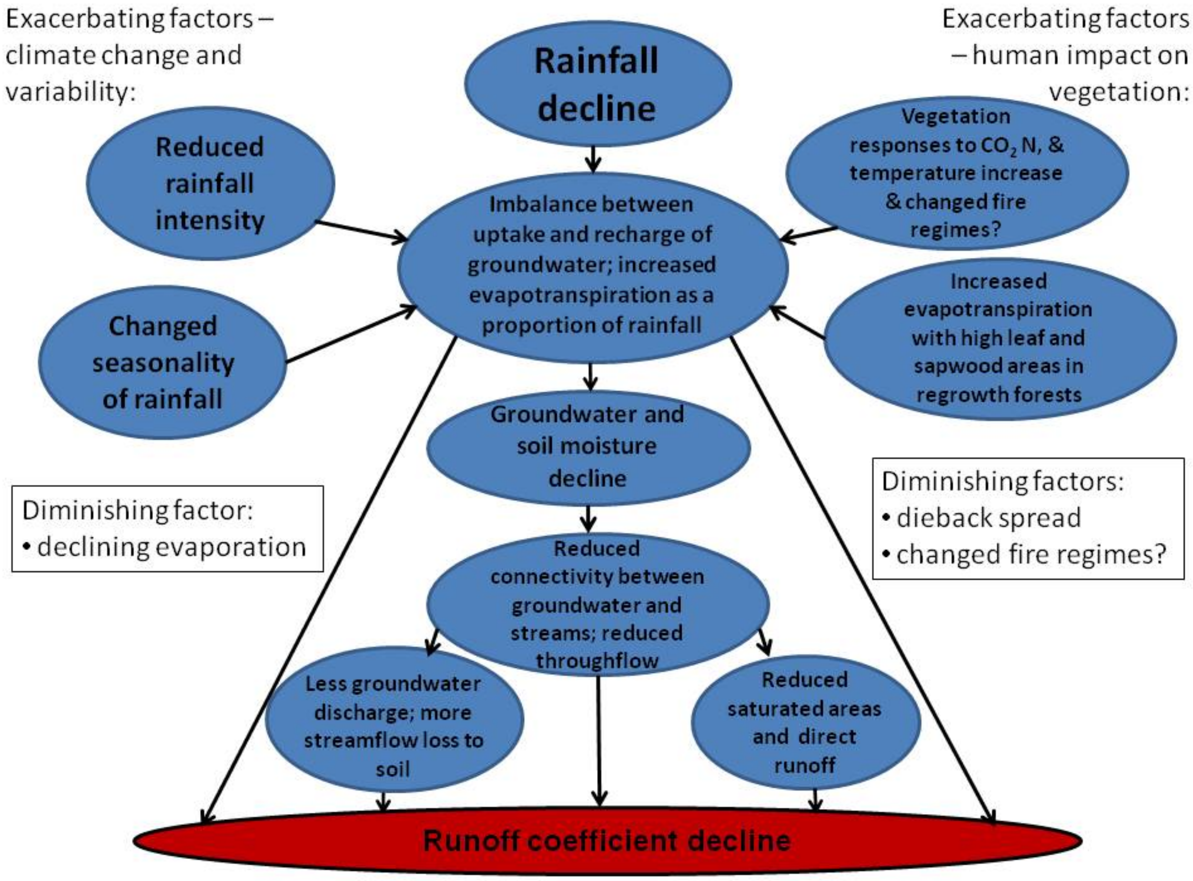

Figure 15 Possible factors contributing to the decline in runoff coefficients

It appears that there is a lag between changes in rainfall and changes in both groundwater levels and the runoff coefficient (Pearcey, pers. comm. 1.07.2009). Thus the hydrology of the water supply catchments may not yet have reached equilibrium, and runoff coefficients may continue to decline, unless rainfall in coming years is much higher than in recent years, or evapotranspiration declines significantly.

Appendix A Groundwater decline

Figures 16 and 17 show the decline in riparian groundwater levels in the Cobiac and Gordon catchments. Note that due to the closure of the Cobiac bore from 1998 to 2005, it is not possible to ascertain whether the decline there has been gradual or step-like.

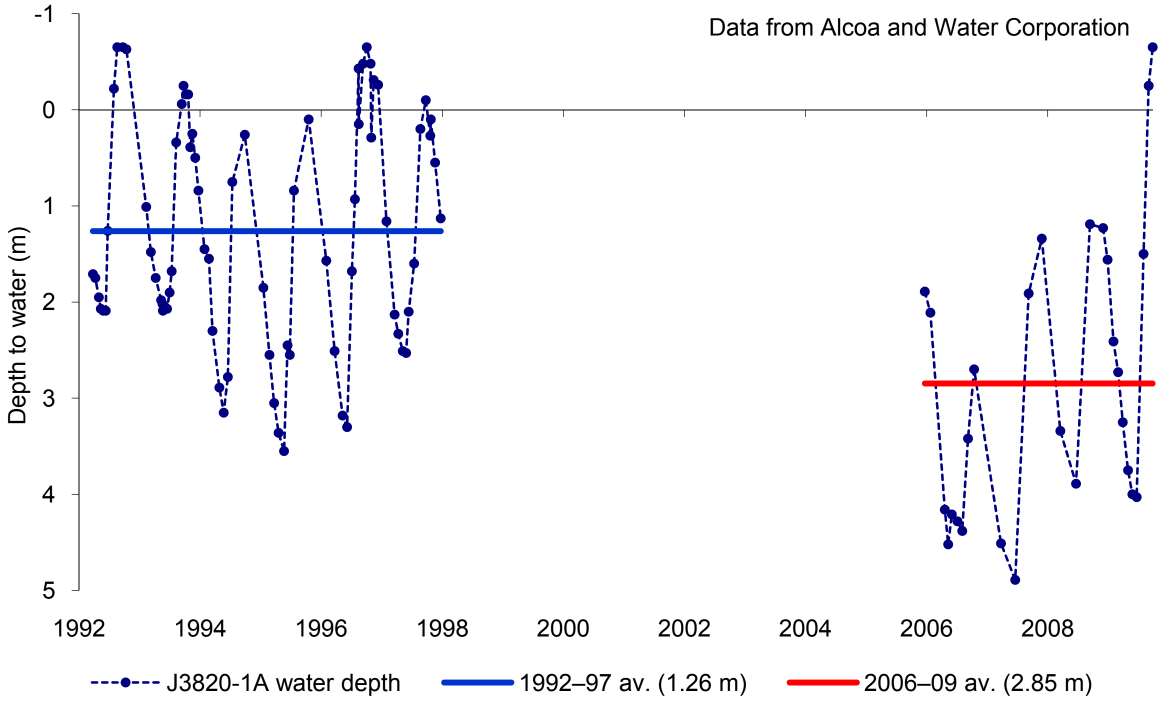

Figure 16 Depth to groundwater in a stream zone piezometer, Cobiac

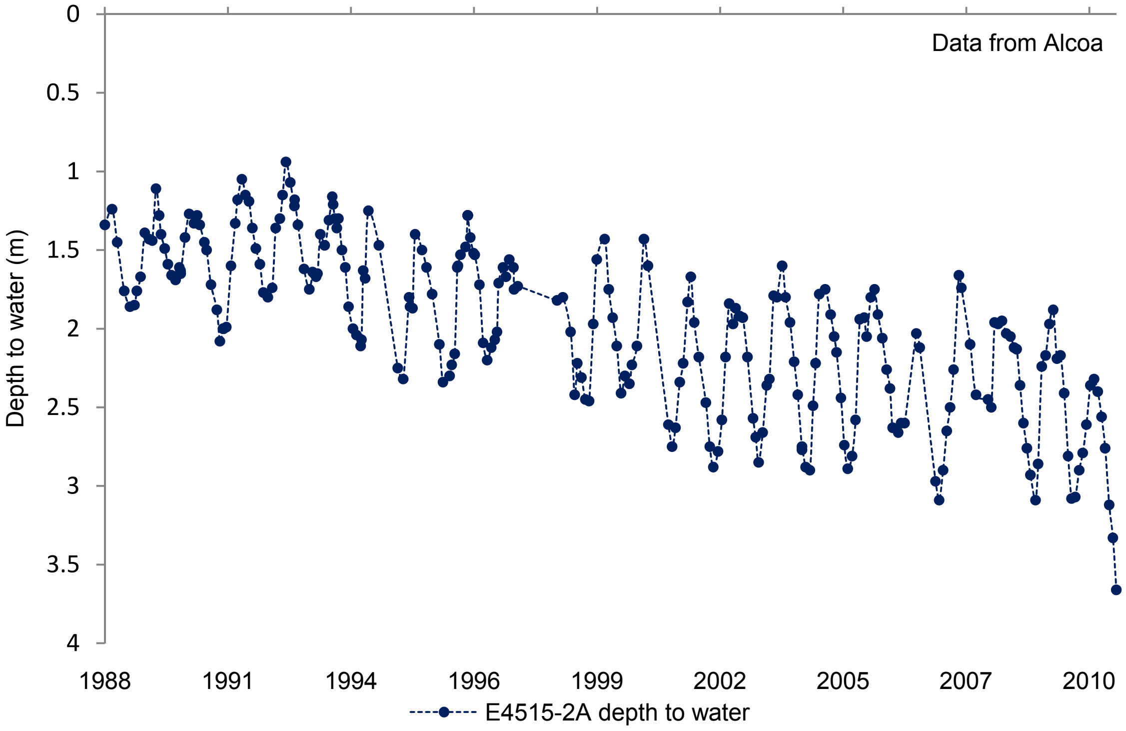

Figure 17 Depth to groundwater in a stream zone piezometer, Bates

Appendix B Rainfall and runoff data

Table 2 Period rainfall, runoff, runoff coefficient averages and autocorrelation

	1950–1974 average			**1975–2000 average**			**2001–2008 average**			**2007**			**Runoff**
	Rainfall (mm)	Runoff (mm)	Runoff coeff. (%)	Rainfall (mm)	Runoff (mm)	Runoff coefficient (%)	Rainfall (mm)	Runoff (mm)	Runoff coeff. (%)	Rainfall (mm)	Runoff (mm)	Runoff coefficient (%)	Auto-correlation? (sig)
Bick	932	201	21.5	769	138	17.9	675	69	10.2	723	63	8.7	Y (0.05)
Cann	1016	85	8.3	833	35	4.3	768	17	2.2	835	23	2.8	Y (0.01)
Chrch	1016	298	29.4	833	179	21.5	768	100	13.0	835	109	13.1	Y (0.01)
Conjur	1153	290	25.1	950	201	21.1	906	101	11.1	1079	105	9.7	Y (0.01)
Nth Dan	1071	226	21.1	951	123	12.9	886	68	7.6	1069	85	7.9	Y (0.01)
Sth Dan	1153	118	10.3	950	62	6.6	906	37	4.0	1079	44	4.1	Y (0.05)
Srp Dam	1071	123	11.4	951	56	5.8	886	27	3.1	1069	40	3.8	Y (0.01)
Srp PH	1015	270	26.6	888	122	13.7	826	58	7.0	998	88	8.8	Y (0.01)
Vict	932	122	13.1	769	83	10.8	675	39	5.7	723	51	7.0	Y (0.05)
Wung	1059	233	22.0	856	150	17.5	806	71	8.9	892	82	9.2	Y (0.01)
Hel.	932	31	3.4	769	13	1.6	675	6	0.8	723	7	1.0	Y (0.01)
L Hel.	932	182	19.5	769	114	14.8	675	49	7.2	723	53	7.3	Y (0.01)
IWSS	1015.0	92.1	9.1	888.4	45.8	5.2	826.4	22.7	2.7	998.2	29.0	2.9	

Table 3 Rainfall at Jarrahdale and total runoff[8] for the water supply catchments

Water year	Rain (mm) May–Oct	Runoff mm/yr	Water year	Rain (mm) May–Oct	Runoff mm/yr	Water year	Rain (mm) May–Oct	Runoff mm/yr
1950	871.4	42.44	1970	1073.3	96.63	1990	765.4	43.41
1951	793	56.2	1971	1080.4	66.44	1991	1118	72.82
1952	1100.2	69.32	1972	806.1	44.32	1992	948	75.17
1953	1091.7	81.1	1973	1262.2	110.84	1993	817.5	36.11
1954	944.8	52.51	1974	1141.6	143.07	1994	793.6	35.96
1955	1241.8	205.75	1975	883.9	58.87	1995	969.3	49.66
1956	949.5	107.92	1976	635.4	30.88	1996	982.5	83.74
1957	912.7	79.2	1977	727.1	22.28	1997	791	31.95
1958	946.4	80.14	1978	949.5	43.84	1998	842	30.77
1959	739.7	27.72	1979	690.9	16.75	1999	1015.2	43.74
1960	803.9	50.41	1980	944.2	36.67	2000	909.4	48.87
1961	854.1	61.15	1981	1058	68.26	2001	684	10.53
1962	996	62.89	1982	752.8	26.08	2002	840.4	23.42
1963	1398.8	181.77	1983	1033.6	75.07	2003	846.6	39.23
1964	1475.6	208.05	1984	962	49.39	2004	818.5	20.55
1965	1138.3	122.05	1985	794.2	33.39	2005	984.1	29.31
1966	825	59.99	1986	856.4	36.4	2006	622.9	9.28
1967	1203.7	138.5	1987	771.8	30.05	2007	998.2	29.05
1968	1132.3	115.79	1988	1158.8	75.53	2008	816.4	20.32
1969	591.9	38.25	1989	928.2	35.11			

---

[8] Note rainfall is for the wet season (May–October), runoff is for the water year (May–April)

Appendix C Rain required to generate streamflow

Figure 18 shows the rainfall from 1 April to the first day of streamflow for three stream gauging stations in the Helena River catchment. The start of the wet season for this analysis is considered to be 1 April (earlier than in the rest of the report) to take into account early winter rains. Rainfall was measured at the Mundaring Weir meteorological station (009031).

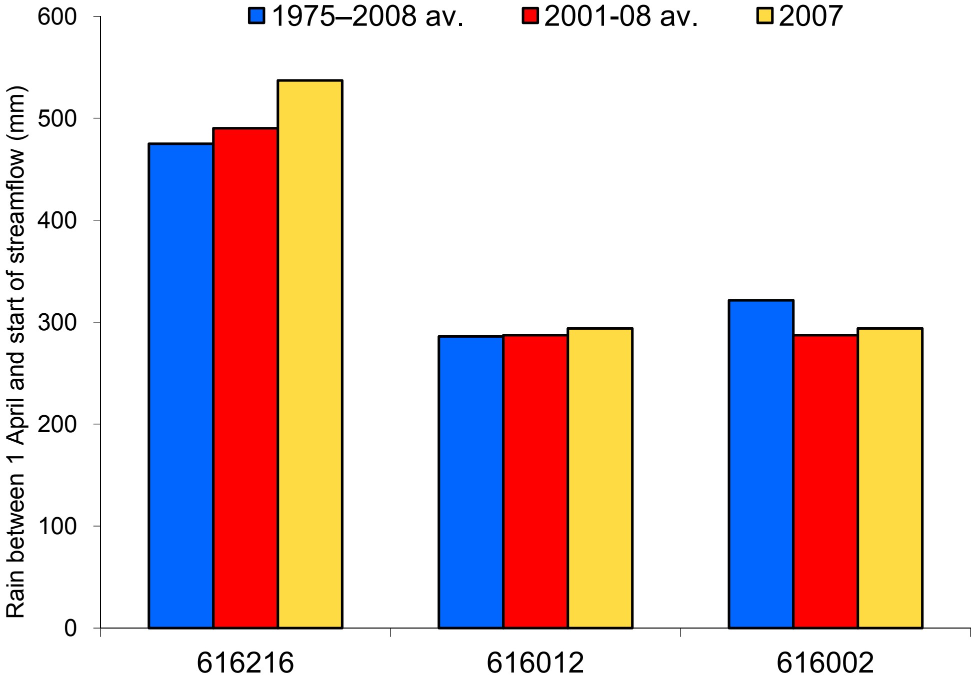

Figure 18 Rain required to generate streamflow

There is no overall trend in the rain required to generate streamflow for these gauging stations. This is probably because these gauging stations are in the eastern low rainfall zone (≤ 850 mm), where groundwater has been disconnected from the stream zone for at least as long as the study period (Mauger et al. 1998; McIntosh, pers. comm. 12.01.2010). In these areas, any decline in groundwater levels is unlikely to significantly affect the rain required to generate streamflow.

Appendix D Mid-winter dry periods

A possible factor contributing to the lower runoff coefficient observed in 2007 may have been dry spells during the wet season causing the catchments to dry out. In such cases, rainfall in the period directly after the dry spell may have been 'used up' in rewetting the catchment, and may not have contributed to catchment runoff.

Here, 2007 is compared with two years that had similar rainfall (Table 4; Figs 19 & 20). March and April are included to take into account any early winter rains.

Table 4 Selected years for dry period comparison

Year	Jarrahdale rainfall (mm)	Total runoff (GL)	Total runoff (mm)	Runoff coefficient (%)	Comment
1996	982	316	84	8.6	Much higher streamflow
1999	1015	164	44	4.3	Higher streamflow
2007	**998**	**109**	**29**	**2.9**	**Study year**

Inspection of the data reveals no significant mid-season dry spells in 2007 compared with 1996 and 1999 to account for the low 2007 runoff.

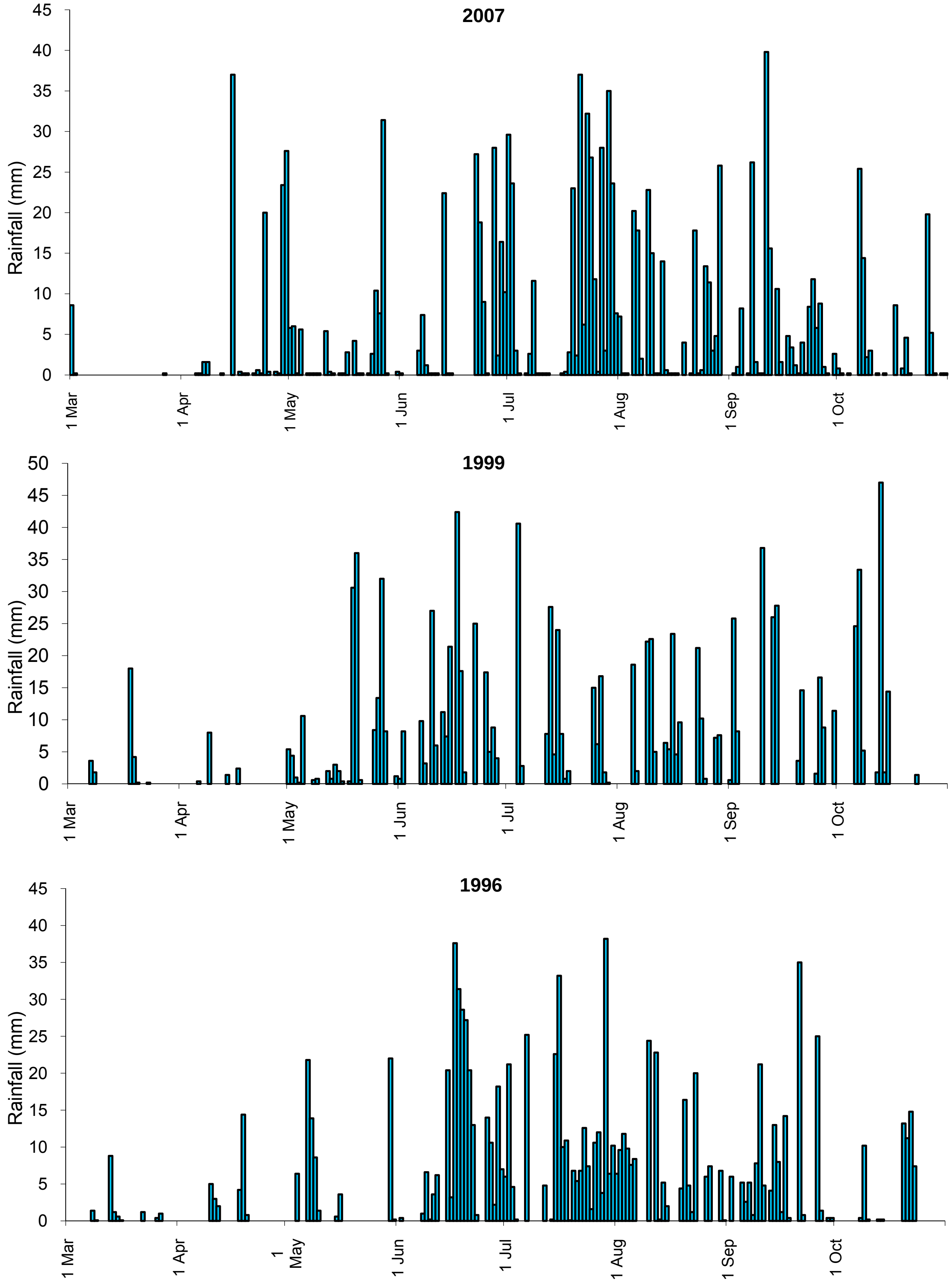

Figure 19 Daily rain records for Jarrahdale (009023)

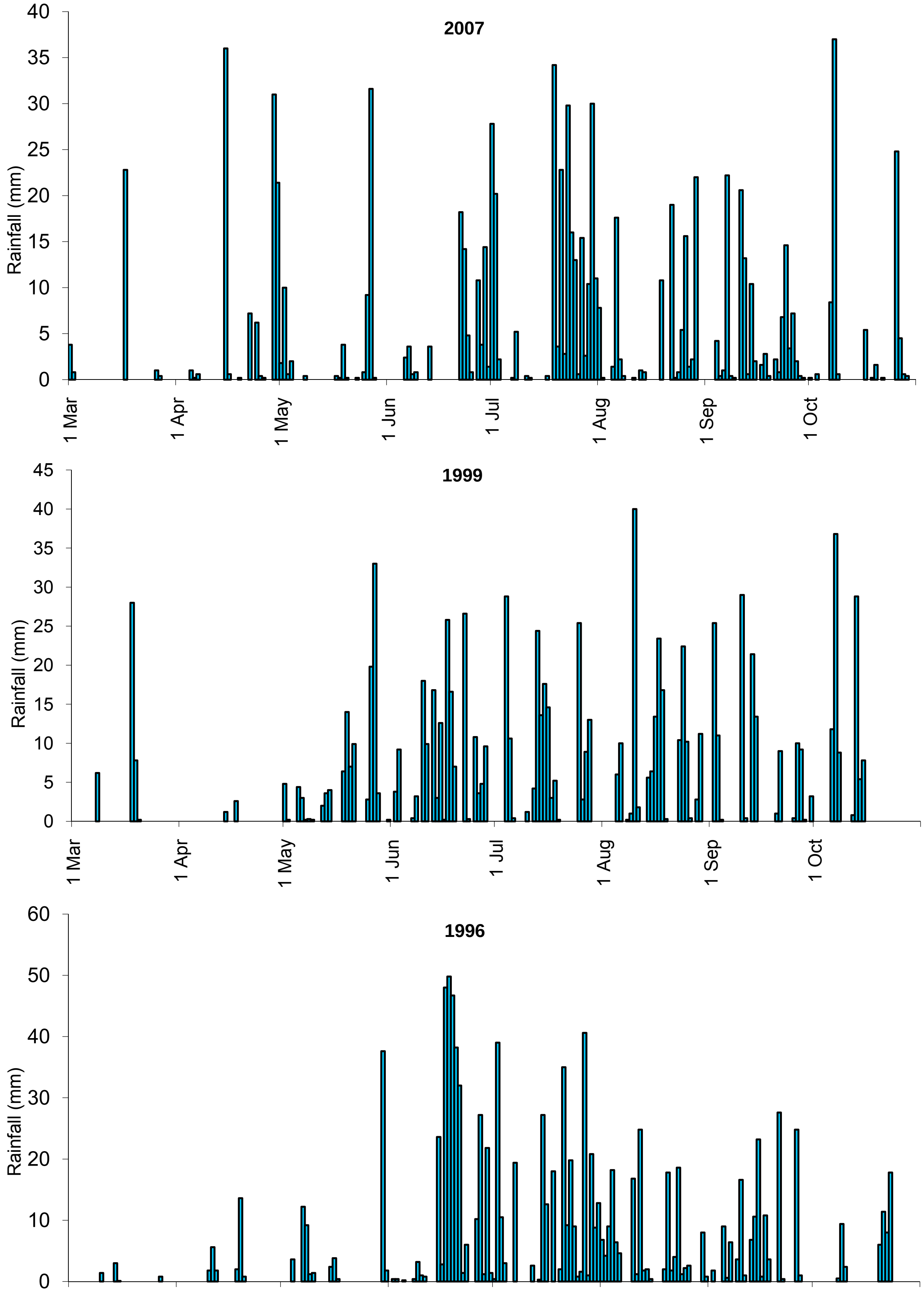

Figure 20 Daily rain records for Mundaring Weir (009031)

Glossary

Auto-correlation	A property displayed by some sequences of adjacent items not being independent of each other; similarity between observations as a function of the time separation between them.
Climate change	Natural and/or anthropogenic long-term, directional trends in climate averages and variability (e.g. in the frequency, severity and duration of extreme events).
Climate variability	Natural, shorter term (daily, seasonal, annual, inter-annual, several years) variations in climate, including the fluctuations associated with El Niño (dry) or La Niña (wet) events. Natural variation does not consist in long-term directional changes in climate averages or variability.
Hysteresis	The lagging of an effect behind its cause. The phenomenon by which an effect in a system depends not only on the present stimulus but also on the previous state of the system.
m AHD	Australian Height Datum, based on the mean sea level around Australia for 1966–68, measured in metres
Rainfall intensity	The amount of rain falling per unit of time (here: an hour)
Runoff	Expressed in millimetres, runoff is a measure of catchment discharge (streamflow out of the catchment) that accounts for the catchment area and makes discharge readily comparable between catchments and with rainfall. It is calculated by dividing catchment discharge by total catchment area (km²).
Runoff coefficient	The proportion of rain that reached the streams and ‘runs off’ a catchment
Percentile	A percentile is the value of a variable below which a certain percent of observations fall; i.e. 90% of a series of data fall under the 90th percentile of that series
Wet season	The months during which most of the rain falls: in this report, May–October

References

Barrett, K 2008, ‘Hydrology for the Wungong catchment trial’ in *Wungong Catchment Trial – research overview*, Water Corporation, Perth.

Chiew, F & Siriwardena, L 2005, *TREND user guide, trend/change detection software*, CRC for Catchment Hydrology, Australia.

Croton, J, Boniecka, LH, Ruprecht, J & Bari, M 2005, *Estimated streamflow changes due to bauxite mining and forest management in the Seldom Seen catchments*, Salinity and land use impacts series, Report no. SLUI 37, Department of Environment, Perth, 45p.

Croton, JT & Dalton, JA 2011, *Review of the trial mining project*, Water and Environmental Consultants report to Alcoa of Australia Limited.

Croton, JT & Reed, AJ 2007, ‘Hydrology and bauxite mining on the Darling Plateau’ *Restoration Ecology,* vol. 15, no. 4, pp. S40–S47.

CSIRO 2009, *Surface water yields in south-west Western Australia*, A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project, CSIRO Water for a Healthy Country Flagship, Australia.

Department of Conservation and Land Management (CALM) 1987a, *Northern forest region: regional management plan 1987–1997*, CALM, Perth.

Department of Conservation and Land Management 1987b, *Northern Forest regional management plan,* Department of Conservation and Land Management, Perth.

Durrant, J 2009, *Streamflow trends in south-west Western Australia,* Surface Water Hydrology Series, Report no. HY 32, Department of Water, Perth.

Grayson, RB, Argent, RM, Nathan, RJ, McMahon, TA & Mein, R 1996, *Hydrological recipes: estimation techniques in Australian hydrology*, Cooperative Research Centre for Catchment Hydrology, Australia, 125p.

Hennessey, KJ, Suppiah, R, Page, CM 1999, ‘Australian rainfall changes 1910–1995’, *Australian Meteorological Magazine,* vol. 48, pp. 1–13.

Hughes, JD, Petrone, KC, & Silberstein, RP 2012, ‘Drought, groundwater storage and stream flow decline in southwestern Australia’, *Geophysical Research Letters*, vol. 39, L03408.

Indian Ocean Climate Initiative (IOCI) 2002, *Climate variability and change in south west Western Australia*, Indian Ocean Climate Initiative Panel, Perth.

Jeffrey, SJ , Carter, JO, Moodie, KB & Beswick, AR 2001, Using spatial interpolation to construct a comprehensive archive of Australian climate data, *Environmental Modelling and Software* 16/4, pp. 309–330.

Li, Y, Cai, W & Campbell, EP 2005, ‘Statistical modelling of extreme rainfall in southwest Western Australia’, *Journal of Climate,* American Meteorological Society, vol. 18, pp. 852–863.

Macfarlane, C, Bond, C, White, DA, Grigg, AH, Ogden, GN & Silberstein, R 2010, ‘Transpiration and hydraulic traits of old and regrowth eucalypt forest in southwestern Australia’, *Forest Ecology and Management*, vol. 260, issue 1, pp. 96–105.

Mauger, GW, Day, JE, & Croton, JT (eds) 1998, *Hydrological and associated research related to bauxite mining in the Darling Range of Western Australia – 1997 review*, Water and Rivers Commission, Water Resource Technical Series, Report no. WRT 26.

McKenzie, NL, May, JE & McKenna, S (eds) 2002, *Bioregional summary of the 2002 biodiversity audit for Western Australia*, Department of Conservation and Land Management, Perth.

Nicholls, N, Chambers, L, Haylock, M, Frederiksen, C, Jones, D & Drosdowsky, W 1999, ‘Climate variability and predictability for south-west Western Australia’, in *'Towards understanding climate variability in south-western Australia', Research reports on the First Phase of the Indian Ocean Climate Initiative, October 1999.*

Peck, AJ, Yendle, PA & Batini, FE 1980, ‘Hydraulic conductivity of deeply weathered materials in the Darling Range, Western Australia’, *Australian Journal of Soil Research,* vol. 18, pp. 129–138.

Petrone, K & Silberstein, R 2009, ‘Streamflow decline in south-west Western Australia: groundwater and surface water threshold response in a changing climate’ in conference proceedings *Climate Change and Resources,* March 2009, Burswood Convention Centre, Perth, CSIRO.

Petrone, KC, Hughes, JD, Van Niel, TG & Silberstein, RP 2010, ‘Streamflow decline in southwestern Australia, 1950–2008’*, Geophysical Research Letters*, vol. 37, L11401.

Reed, A 2008, ‘Groundwater responses of the Cobiac hydrological research catchment’ in *Wungong Catchment Trial – research overview*, Water Corporation, Perth.

Rogers, SJ & Ruprecht, JK 1999, *The effect of climate variability on streamflow in the south-west of Western Australia*, Surface Water Hydrology Series, unpublished report, SWH 25, Water and Rivers Commission, Perth.

Ruprecht, J & Pearcey, M 1999, *Surface water hydrology: an introduction*, Surface Water Hydrology Series, unpublished report no. SWH 26, Water and Rivers Commission, Perth.

Ruprecht, JK & Schofield, NJ 1989, ‘Analysis of streamflow generation following deforestation in the south-west of Western Australia’, *Journal of Hydrology,* vol. 105, pp. 1–17.

Schofield, NJ 1984, ‘A simulation model predicting winter interception losses from reforestation stands in South-west WA’, *Australian Forest Research,* vol. 14, pp. 105–127.

Silberstein, RP, Macfarlane, CK, Petrone, K, Hughes, J, Dawes, WR, Lambert, P, Li, M, Wallace, JF, Ogden G, Smart, N, Aryal, SK 2011, *Streamflow and vegetation dynamics under a changing climate and forest management. Final report to WA Water Foundation on project 041-05,* CSIRO Water for a Healthy Country National Research Flagship, Canberra.

Stern, H, de Hoedt, G & Ernst, J 2000, ‘Objective classification of Australian climates’, *Australian Meteorological Magazine,* vol. 49, pp. 87–96.

Water Corporation 2008a, *Wungong Catchment Trial; four yearly review for the Conservation Commission of Western Australia*, Water Corporation, Perth.

Water Corporation 2008b, *Water Forever: Options for our water future,* Water Corporation, Perth.

Department of Water

168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842
Phone: (08) 6364 7600
Fax: (08) 6364 7601
www.water.wa.gov.au

7346/0/0912