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Statistical characterisation and attribution of recent rainfall and runoff in the Murray-Darling Basin

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Abstract:

It is widely recognised that the Murray-Darling Basin (MDB) in south-eastern Australia has been in the grip of a serious drought for many years. Over the period 1997−2006, mean annual rainfall has been approximately 16 percent lower than the long-term (1895−2006) average across the MDB. Runoff has been 39 percent lower over the same period.

The continuing drought in the MDB has brought the need for a thorough understanding of how the current drought compares to the longer-term variability of rainfall and runoff in the MDB. In this paper, we: (1) examine the historical variability of annual rainfall and runoff in the MDB using a statistical "change-detection" methodology; (2) quantify, in a probabilistic sense, the severity of the recent dry sequence using average recurrence intervals (ARIs); and (3) quantify the hydroclimatic causes of low runoff in the southern MDB, using the Campaspe basin as a representative example, with the lumped conceptual daily rainfall-runoff model SIMHYD and four scenarios of rainfall and potential evapotranspiration.

In terms of annual rainfall and runoff in the MDB, the largest signal is an increase in both rainfall and runoff after the mid-1940s. However, a closer analysis using a multiple change-point test identifies several other dry sequences, notably at the start of the twentieth century (the "Federation drought"), a long period of low rainfall around 1936−1945, and the ten years of 1997−2006. Most of the MDB demonstrates a downward trend in rainfall since 1950, with practically no upward trends in rainfall detectable after the 1970s.

Over the period 1997−2006, rainfall and runoff are substantially lower over much of the MDB. This lower rainfall and runoff is predominant in the north-east part of the MDB and the southernmost parts. In the southern MDB, the average recurrence intervals of the reductions in rainfall are mostly 20−50 years, with small areas having ARIs more than 100 years. In the southern MDB, the average recurrence intervals of the runoff reductions over 1997−2006 are much larger than the corresponding average recurrence intervals for rainfall reductions, with large areas of the southern parts of the MDB having ARIs greater than 300 years, which indicates that the recent runoff reduction is larger than expected based on the reduction in annual rainfall alone. Several reasons have been suggested for this including: larger proportional decreases in autumn and winter rainfall; higher temperatures; and less interannual variability of rainfall compared to previous dry sequences.

We attribute the lower runoff to these hydroclimatic features of the recent dry sequence, and find that the changed seasonality of rainfall has the largest effect on runoff, followed by historical variability (which includes interannual variability) of rainfall, then higher potential evapotranspiration. Using this attribution methodology we explain 71% of the observed reduction in runoff over 1997−2006. The residual is most likely attributable to interactions between different effects.

Keywords: *Rainfall, runoff, Murray-Darling Basin, drought.*

1. INTRODUCTION

It is widely recognised that the Murray-Darling Basin (MDB) in south-eastern Australia has been in the grip of a serious drought for many years. Over the period 1997−2006, mean annual rainfall has been approximately 16 percent lower than the long-term average across the MDB. Runoff has been 39 percent lower over the same period [*Potter et al.*, 2008]. Climate change projections generally suggest that rainfall will decrease over the Murray-Darling Basin in the future [*Chiew et al.*, 2008a; *CSIRO and Bureau of Meteorology*, 2007]. Low annual rainfall, together with increased temperatures and potential evapotranspiration, decreased autumn and winter rainfall in a region with largely winter-dominated runoff and decreased interannual variability of rainfall, have combined to yield unprecedented reductions in runoff in the southern MDB. In this paper, we place the current drought in the context of the long-term historical hydroclimate series and compare the rainfall and runoff characteristics in the current drought with similar dry periods in the past.

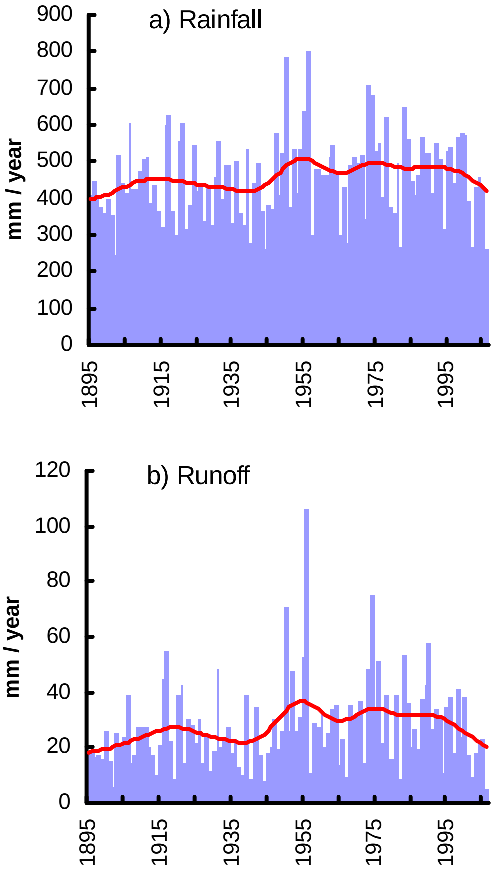

Figure 1. Annual a) rainfall and b) runoff in the Murray-Darling Basin.

2. HISTORICAL RAINFALL AND RUNOFF

Figure 1 shows annual rainfall and runoff in the Murray-Darling Basin over the period 1895−2006. The rainfall and runoff data are spatial averages of 40475 grid cells at 0.05° x 0.05° resolution across the MDB. The rainfall data are annual totals of the SILO data drill for rainfall [*Jeffrey et al.*, 2001]. The runoff data are annual totals of SIMHYD modelled daily runoff. Areal potential evapotranspiration used to model runoff is calculated using Morton's wet environment evapotranspiration algorithms [*Chiew et al.*, 2008b]. The red lines in **Figure 1** show the low-frequency variability of rainfall and runoff over the historical record. These were calculated using a two-sided Gaussian kernel smoother, similar to moving average filters of the data, but with more weight given to nearby years.

The largest signal in the low-frequency variability of the rainfall and runoff data is a step-change after the mid-1940s. Three prominent dry periods are evident from **Figure 1**: at the start of the record, between 1935 and 1945, and at the end of the record. Application of the "cumulative deviation" change-point test (**Figure 2**) to the annual rainfall data identifies a statistically significant change-point for rainfall in 1946, and for runoff in 1949. However, there are clearly other fluctuations in the rainfall and runoff in the MDB. By applying a sequential t-test, i.e. repeatedly applying the t-test after removing significant differences in the median from the time series, other wet and dry sequences can be identified. The results identify a drought at the beginning of the rainfall data by the relatively large number of upward step changes in the 1900s and 1910s. There are several downward step changes identified in the 1920s and 1930s corresponding to the 1936–1945 drought and the dry sequences that preceded this in the 1920s. Since the 1970s, there are almost no upward step changes in rainfall, only downward step changes. So, although recent rainfall has been significantly lower in parts of the MDB, and this can be identified using the multiple change-point test, this signal is generally not identified in the single change-point tests because of the large upward step-change in rainfall in the mid-1940s in much of the MDB.

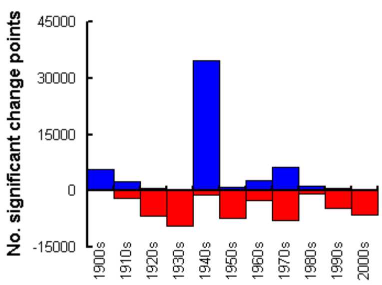

Figure 2. Number of significant change points (out of 40475 grid cells) with positive (above axis) and negative (below axis) step changes.

3. RECENT TRENDS IN RAINFALL AND RUNOFF

Rainfall over most of the Murray-Darling Basin since the mid-1940s has been declining, with the biggest declines (up to 3−4 mm per year) in the southern and south-eastern parts of the MDB [*Bureau of Meteorology*, 2009]. Averaged across the MDB over the period 1997−2006, mean annual rainfall has been approximately 16 percent lower than the long-term average, while runoff has been 39 percent lower over the same period. **Figure 3** shows the percentage difference between mean annual rainfall and runoff in 1997−2006 compared to 1895−2006. In most of the southern half of the MDB, and a small area in the north-eastern MDB, rainfall is more than 10% lower than the 1895−2006 mean, and runoff is more than 30% lower. The southernmost parts show even larger decreases with rainfall showing between 10% and 20% reduction and runoff showing a greater than 50% reduction, and these areas are statistically significantly different from the long-term mean based on Student's t-test and rank-sum tests.

Research into the causes of this rainfall reduction over the southern MDB, and the role of regional climatic features, has identified correlations between longer term variability of rainfall and several climatic indices such as El Niño-Southern Oscillation, Southern Annular Mode, Indian Ocean sea surface temperatures and the location and intensity of the sub-tropical ridge, which controls the northerly movement of low-pressure systems over southern Australia [*Murphy and Timbal*, 2007]. Notably, rainfall anomalies in autumn and winter in south-eastern Australia are related to the intensity of the sub-tropical ridge, which has been shown to be strongly linked to global annual surface temperature [*Timbal et al.*, 2007].

The reduction in runoff over the last ten years of the historical data is unprecedented [*Potter et al.*, 2008]. During the seven-year period of October 2001 to September 2008, rainfall has been only slightly higher over the MDB than the lowest recorded seven-year period since 1900 [*Bureau of Meteorology*, 2008]. However, inflows into the MDB during 2006 were the lowest in 117 years of records from the Murray-Darling Basin Commission. As of November 2008, inflows into the MDB have been below average for 37 consecutive months [*Murray-Darling Basin Commission*, 2006].

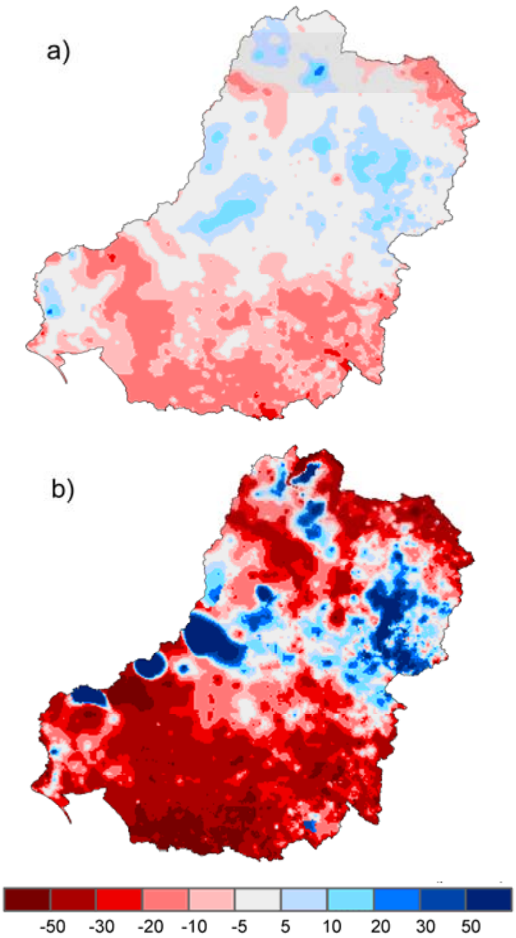

Figure 3. Percentage difference between a) mean annual rainfall and b) mean annual runoff in 1895–2006 and in 1997–2006.

The severity of the observed reductions in recent rainfall and runoff can be assessed in a probabilistic sense using average recurrence intervals (ARIs). In a general sense, the ARI measures the expected time between two equally severe hydrological events. We calculated ARIs for rainfall and runoff over the last ten years of data using a simulation approach. We used the lag-one autoregressive model of *Frost et al.* [2007] to generate 100 replicates of 100,000 years of annual rainfall and runoff for each grid cell. The ARI for the last ten years of rainfall and runoff for each grid cell were calculated directly from each replicate of rainfall and runoff; the ARI was then taken as the median ARI from the 100 replicates. Further details on the method used to calculate rainfall and runoff ARIs are provided by *Potter et al.* [2008]. Results are shown in **Figure 4**.

The spatial pattern of average recurrence intervals closely resembles the pattern of reductions of rainfall and runoff shown in **Figure 3**. Rainfall over 1997−2006 has an ARI of mostly 20−50 years in the north-eastern and southern parts of the MDB, and more than 100 years in the southernmost parts. The ARIs elsewhere are generally less than 20 years, suggesting that there are several other ten-year rainfall averages similar to 1997−2006 rainfall. For runoff over 1997–2006, the southern fringes of the MDB have ARIs greater than 300 years. The area with 1997–2006 runoff ARIs greater than 100 years extends further into the interior than the areas with 1997–2006 rainfall ARIs greater than 100 years. For most of the remainder of the MDB, the runoff ARIs are

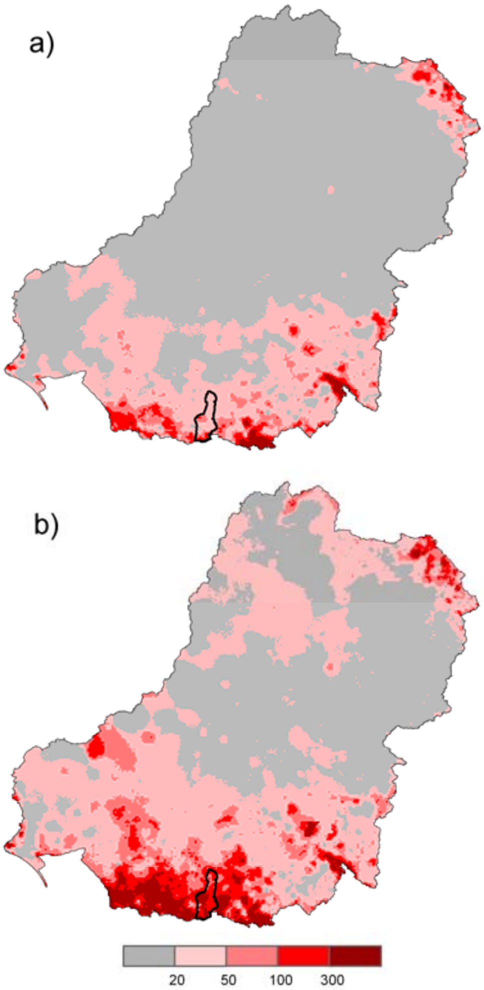

Figure 4. Average recurrence intervals (years) for a) rainfall and b) runoff over 1997−2006. The Campaspe river basin (discussed in section 4) is outlined in black.

generally of the same magnitude as the rainfall ARIs. This indicates that runoff in the southern MDB is lower than expected over 1997–2006 based solely on the reduction in annual rainfall in the southern MDB over 1997–2006.

4. ATTRIBUTION OF LOW RUNOFF IN THE CAMPASPE

In this section we use the lumped conceptual SIMHYD daily rainfall-runoff model to attribute hydroclimatic reasons to the lower than expected runoff in the southern MDB. We focus on the Campaspe river basin (outlined black in **Figure 4**), which is representative of the region of the southern MDB with lower than expected runoff over 1997−2006.

Table 1 shows the mean rainfall and runoff in the Campaspe over the three ten-year dry sequences 1895−2004, 1936−1945 and 1997−2006. Note that rainfall in the Campaspe during 1936−1945 was actually lower than rainfall during 1997−2006, but runoff was comparatively higher. The long-term elasticity of runoff to rainfall in the Campaspe is 2.52 (calculated with the median-based method described by *Chiew* [2006]). Runoff elasticity measures the expected percentage reduction in annual runoff resulting from a unit percentage reduction in annual rainfall, based on the co-variability of observed annual rainfall and runoff anomalies. So, based on the long-term runoff elasticity in the Campaspe and the observed rainfall reduction (**Table 1**), we expect a runoff reduction in 1997−2006 of only 32.5% (or 21.0 mm). Several reasons have been suggested for the lower than expected runoff in the southern MDB [*Nicholls*, 2004; *Murphy and Timbal*, 2007; *Cai and Cowan*, 2008]. These include:

1. Larger proportional reductions in autumn and winter rainfall in recent years compared to previous dry sequences (**Figure 5**);
2. Increased temperature and potential evapotranspiration (**Table 1**); and
3. Less variability of annual rainfall and winter rainfall, particularly compared with the dry sequence in 1936−1945 (**Table 1**).

The relative contribution of these characteristics of the recent dry sequence to the observed runoff decline is estimated using the lumped conceptual daily rainfall-runoff model SIMHYD with Muskingum routing calibrated to streamflow data from 240 small and medium size unregulated gauged catchments across the MDB [*Chiew et al.*, 2008b]. The calibration period was chosen as 1975–2006, which accounts for climatic variability as well as current development (land use). In the model calibration, the six parameters of

Table 1. Mean rainfall and runoff (mm) in the Campaspe river basin over the long-term (1895−2006) and three selected ten-year dry sequences.

	Mean rainfall	(% diff.)	CV of annual rainfall	Mean monthly CV of winter rainfall	Mean runoff	(% diff.)	Mean PET	(% diff.)
1895–2006	594		0.25	0.48	64.5		1188	
1895–1904	519	(-12.7%)	0.16	0.48	35.3	(-45.3%)	1209	(+1.8%)
1936–1945	483	(-18.7%)	0.39	0.53	46.5	(-28.0%)	1190	(+0.2%)
1997–2006	517	(-12.9%)	0.21	0.43	29.0	(-55.1%)	1211	(+1.9%)

SIMHYD are optimised to maximise the Nash-Sutcliffe efficiency of daily runoff together with a constraint to ensure that the total modelled runoff over the calibration period is within 5 percent of the total recorded runoff. The runoff for grid cells that are not within a calibration catchment is modelled using optimised parameter values from the geographically closest grid cell which lies within a calibration catchment. The SIMHYD model reproduced satisfactorily the runoff over the Campaspe and the daily runoff series simulated by SIMHYD is similar to the runoff series simulated by several other rainfall-runoff models (Sacramento, IHACRES, SMARG – not shown here).

Four scenarios of rainfall and potential evapotranspiration were considered. The first three scenarios are transformations of observed 1997−2006 rainfall and potential evapotranspiration, whereas the fourth scenario is the average runoff resulting from a transformation of all 102 ten-year blocks of calendar data between 1895−1904 and 1996−2005. These four scenarios are:

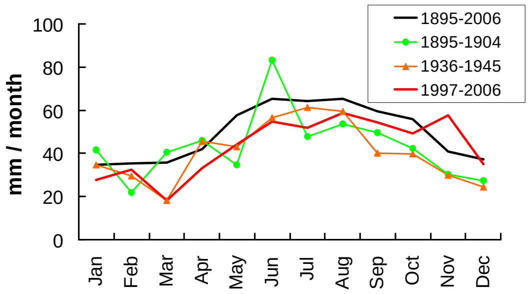

Figure 5: Mean monthly rainfall in the Campaspe over 1895−2006 and during the three ten-year dry sequences.

1. **Scaled rainfall scenario.** Scale observed 1997−2006 rainfall to have mean annual rainfall equal to long-term mean annual rainfall. Runoff from this scenario estimates the effect solely from the observed reduction in mean annual rainfall only.
2. **Seasonally scaled rainfall scenario.** Scale observed 1997−2006 rainfall by month to have mean monthly rainfall proportional to the long-term mean monthly rainfall seasonality, but preserving the magnitude of the observed 1997−2006 mean annual rainfall reduction. Runoff from this scenario estimates the effect from the larger proportional reductions in the runoff-producing autumn and winter months.
3. **Scaled potential evapotranspiration scenario.** Scale observed 1997−2006 potential evapotranspiration time series to have mean annual potential evapotranspiration equal to long-term mean annual potential evapotranspiration. Runoff from this scenario estimates the effect of recent increases in potential evapotranspiration.
4. **Historical variability scenario.** For a given ten-year block of historical rainfall, scale observed rainfall to have mean monthly rainfall equal to 1997−2006 mean monthly rainfall. Use observed 1997−2006 potential evapotranspiration. Runoff averaged across all ten-year blocks estimates the effect of rainfall variability at different timescales, from changes in the daily sequencing of rainfall events, changes to the daily rainfall distribution, as well as interannual variability of rainfall.

Figure 6 demonstrates the rainfall transformations for the first two rainfall scenarios for an example grid cell in the Campaspe. The scaled rainfall scenario preserves the 1997−2006 observed monthly progression of rainfall but has mean annual rainfall equal to the long-term mean, whereas rainfall in the seasonally scaled rainfall scenario preserves the 1997−2006 observed reduction in mean annual rainfall, but forces the monthly progression of rainfall to follow the long-term mean. Mean monthly rainfall of each 10-year block from the historical variability scenario follows observed 1997−2006 mean monthly rainfall (red line in **Figure 6**).

Table 2 shows that the increased runoff under the scaled rainfall scenario compares favourably to the expected reduction in runoff based on the observed reduction in rainfall and the long-term elasticity of runoff to rainfall in the Campaspe (as described above). The largest secondary effect on runoff is from the seasonally scaled rainfall scenario. Under this scenario, where the monthly scaling factors are larger in the autumn and winter months compared with the spring and summer months (**Figure 6**), the lower potential evapotranspiration rates in autumn and winter lead to higher soil moisture levels and thus more runoff. The direct effect on runoff of increased temperatures is lower than the effect of changes in rainfall because runoff is more sensitive to changes in rainfall than to changes in potential evapotranspiration [*Chiew*, 2006], also the observed rainfall anomaly is

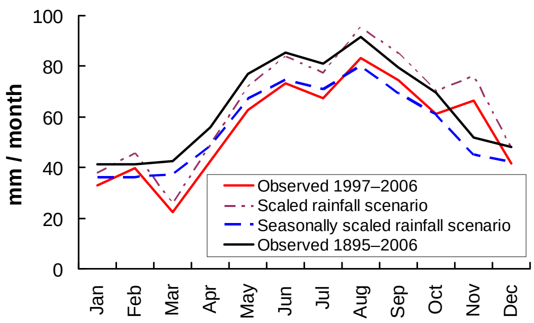

Figure 6. Average monthly rainfall for an example grid cell in the Campaspe under scaled rainfall and seasonally scaled rainfall scenarios.

much larger than the potential evapotranspiration anomaly. However, as noted above, increased temperatures may be linked (either causally or associatively) to more general large-scale climatic patterns, such as the location and intensity of the sub-tropical ridge in southern Australia. Thus the indirect effect of increased temperatures on runoff may be greater than the direct effect of 1.1 mm reported in **Table 2**. The size of the temperature effect is also dependent on the formulation of potential evapotranspiration used in the modelling.

Table 2: Runoff results from different rainfall and potential evapotranspiration scenarios considered in the Campaspe. Runoff produced under scenarios is over 1997–2006.

Scenarios	Modelled runoff	Additional runoff	Percent of reduction explained
Scaled rainfall	49.4	20.4	57.5%
Seasonally scaled rainfall	30.9	1.9	5.4%
Scaled potential evapotranspiration	30.1	1.1	3.1%
Historical variability	30.9	1.9	5.3%
Sum of all scenarios	54.3	25.3	71.2%
Residual		10.2	28.8%

Since, by definition, each ten-year block of rainfall in the historical variability scenario has both mean annual rainfall as well as mean monthly rainfall equal to the 1997–2006 means, changes in runoff must come from variability at the daily scale (timing and distribution) and longer term (interannual) scale. **Figure 7** shows that runoff from the historical variability scenario closely follows interannual changes in the standard deviation of annual rainfall up until about 1961–1970; modelled runoff drops off afterwards, signifying that changes to rainfall at other timescales may become more important, e.g. changes at the daily timescale. Runoff from the historical variability scenario around 1936–1945 is nearly 11 mm larger than observed 1997–2006 runoff. This is connected to a large increase in the standard deviation of annual rainfall in the 1936–1945 block of rainfall, which explains the majority of the relatively low runoff reduction during 1936–1945 shown in **Table 1**.

Runoff from the sum of all scenarios is calculated by summing the additional runoff column. This additional runoff is then added to the mean runoff observed over 1997–2006. Residual runoff is then the difference between long-term mean runoff and runoff from the combination of all four scenarios. At least part of the residual runoff reduction of 10.2 mm may be attributable to interactions. For example, the effect of a reduction in autumn and winter rainfall (as measured by the seasonally scaled rainfall scenario in **Table 2**) is likely to be higher when mean annual rainfall is higher (scaled rainfall scenario). Also, note that the results presented above are modelled responses to hypothetical scenarios. The rainfall-runoff modelling allows the quantification of the effects of different scenarios, but is also limited to the way we conceptualise processes through the assumptions of the rainfall-runoff modelling. During extreme weather events, such as droughts, our understanding of the underlying hydroclimatic processes as embodied in the modelling assumptions based on observation of "normal" conditions may differ from the actual hydroclimatic behaviour of a catchment, such as higher runoff sensitivity to temperature, and loss of surface-groundwater connectivity.

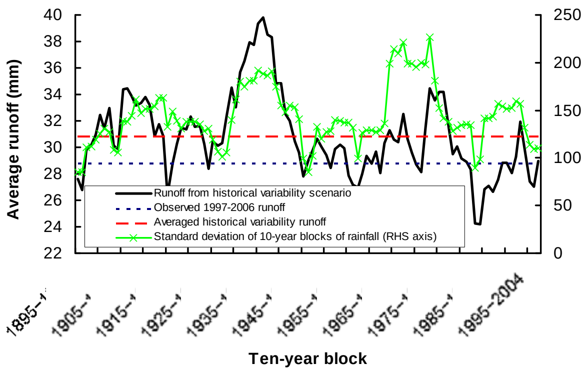

Figure 7: Average runoff from the historical variability scenario for each ten-year block of rainfall (left-hand axis), and annual standard deviation of 10-year rainfall blocks (right-hand axis).

5. CONCLUSIONS

The largest signal in rainfall and runoff in the Murray-Darling Basin is a step change occurring around the mid-1940s. Several dry sequences are identifiable using a multiple change-point test, particularly the three ten-year dry sequences of 1895–1904, 1936–1945 and 1997–2006. The dry sequence of 1997–2006 is mostly concentrated in the southernmost parts of the MDB where average recurrence intervals for rainfall reductions are estimated mostly at 20–50 years, with some areas exceeding 100 years. Runoff reductions in the same area are much larger than for rainfall with some areas having average recurrence intervals for runoff exceeding 300 years. The largest secondary (i.e. apart from the annual reduction in rainfall) effect on runoff is from proportionally larger reductions in rainfall during the autumn and winter months. Historical variability (both day-to-day and interannual) of rainfall and increased temperatures also play a role in the recent runoff reductions in the Campaspe.

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