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Changing climate and the uncertainties in allocating water for consumptive and environmental needs in highly developed catchments

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Abstract: Hydrological modelling and ecological assessment were recently undertaken to inform the review of the Water Allocation Plan for the Barossa Prescribed Water Resources Area in South Australia. The Landscape South Australia Act 2019 requires that a plan "must set out principles associated with the determination of water access entitlements and for the taking and use of water so that: (i) an equitable balance is achieved between environmental, social and economic needs for the water; and (ii) the rate of the taking and use of the water is sustainable". Essentially, a Water Allocation Plan is required to set out sustainable extraction limits, with water to be allocated for the present and future environmental, social, cultural and economic needs of water within those limits.

The Water Allocation Plan ('the Plan') for the Barossa Prescribed Water Resources Area ('the Area'), adopted in 2009 is currently being reviewed. As part of the review, a series of scientific investigations were undertaken to improve understanding of the behavior of the water resources. Of particular importance is selecting an appropriate climate period as the two fundamental metrics in establishing environmentally sustainable extraction limits in a plan – the resource capacity and the environmentally critical flow regime – vary based on climate periods. Historically, such selections were generally based on the longest period of rainfall and streamflow data availability, with rainfall records spanning from the early 1900s and streamflow records from late 1960s. The 2009 Barossa Plan used streamflow data for the climate period from the late 1960s to 2006. Resource capacity was then quantified to be the average annual flow for the period, with the impacts of development removed through modelling.

This practice of using historic average annual flows to establish the resource capacity has been reconsidered under the context of a changing climate, uncertainties around future climate, and their implications to rainfall-runoff response. Consequently, a climate period that has a stronger focus on the recent climate and takes into account the effects of the Millennium drought, post-drought climate, and future climate projections has been used.

This climate modelling undertaken by the South Australian Department for Environment and Water and Adelaide University, projects a drier and hotter future climate for the area. The results from this modelling also show that changes to rainfall seasonality and pattern are expected alongside decreasing long-term average annual rainfall totals. These changes have direct and non-linear effects on runoff generation processes that affect surface water availability (quantity and flow regime) within the area. Further, extensive analyses of recent rainfall records for the area also indicate a shift in rainfall pattern since the beginning of the Millennium drought, providing evidence of a statistically significant 'shift' or 'step change' in annual and seasonal rainfall patterns shown by the climate modelling. This shift aligns with the climate projection modelling undertaken previously and with recent annual rainfall indicating a higher variability in the frequency of extremely dry (2018 and 2019) and wet years (2022).

This paper presents the results of these investigations providing evidence of a possible shift in rainfall patterns since the beginning of the Millennium drought; its impacts on the area's rainfall-runoff response and environmentally significant flow regimes. These results require selection of an appropriate climate period that accounts for a changing climate to establish surface water resource capacity and environmental water requirement flow regimes for the area in the amended Plan, as well as, indicating that similar consideration be given in other areas experiencing similar conditions of changing climate.

Keywords: *Climate change, catchment hydrology, water allocation plans, aquatic ecosystems*

1. INTRODUCTION

The Barossa area (Figure 1) is a world-renowned premium food, wine and agricultural region located around 60 km north-east of Adelaide in South Australia. The Barossa Prescribed Water Resources Area ('the Area') is a sub-catchment of the North-Para River catchment and covers an area of 383 km^2. The topography of the region varies from the gently sloping plains of the valley floor, through to the undulating hills of lower Flaxman Valley and Duck Ponds Creek, to the steeper and more elevated areas of Tanunda Creek and Jacob Creek (Jones-Gill and Savadamuthu, 2014). The area has been extensively cleared, with remnants of native vegetation only found in relatively small, isolated conservation areas. Numerous large private surface water storages (farm dams) have been constructed since the late 1970s, leading to a reduction in flows and changes to the flow regime (Jones-Gill and Savadamuthu, 2014, DEW, 2022).

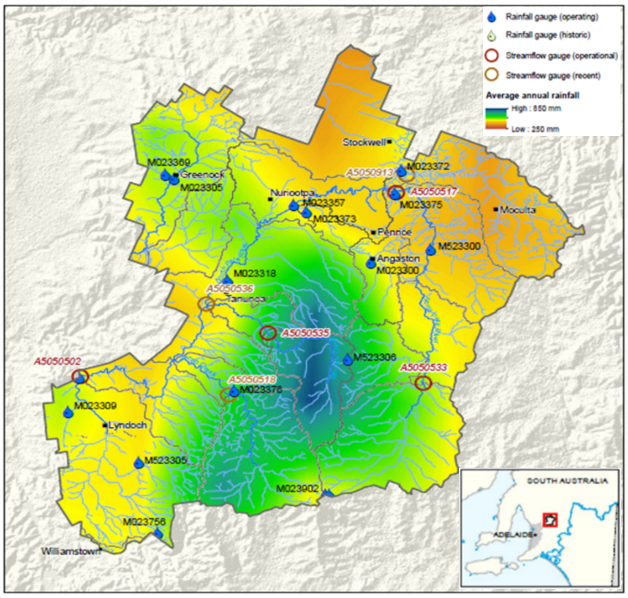


Figure 1. Barossa rainfall and streamflow monitoring sites

The Area experiences a dry and highly variable Mediterranean climate, with consequent seasonal rainfall and streamflow patterns. Rainfall varies throughout the Area from approximately 850 mm in the headwaters to around 300 mm in the plains, with much of the rainfall and flows occurring during the period of June to October and remaining predominantly dry outside of this period. Surface water runoff generated in the headwaters is intercepted by high-density, unregulated private farm dams that were developed prior to the resource being prescribed. Further downstream, flows are diverted and/or extracted directly from watercourses for irrigation, stock and domestic, and other human needs. These interceptions and extractions have caused significant reduction in flows and alteration of the flow regime. Since the Area became prescribed, there has been no new dam development or additional extraction of surface water allowed.

The surface and ground water resources in the Area support extensive aquatic ecosystems in the form of numerous permanent pools and springs that are considered environmental assets. While the aquatic ecosystems of the Barossa are considered degraded, there are isolated areas of better conditions (Green et al. 2014), linked to areas of high rainfall/low development or areas of high groundwater inputs. In the Barossa, alteration of the flow regime has resulted in a communities dominated by tolerant generalist species of macroinvertebrates and alien fish species such as Eastern Gambusia (*Gambusia holbrooki*) and Redfin Perch (*Perca fluviatilis*).

Climate projection models predict a drier climate future for the Area (Leigh et al., 2022; DEW, 2022), with recent rainfall observations consistent with this prediction. These changes in rainfall have already had a direct impact on both the security of supply to water users and the components of the flow regime that are critical to functionality of the ecological process of water-dependent ecosystems. Combined with the projected reduction in annual rainfall totals and continuing changes in rainfall patterns indicate that both a further reduction in total catchment yield and changes to streamflow patterns are likely.

A Water Allocation Plan for the Area was adopted in 2009 ('the 2009 Plan') (Natural Resources AMLR, 2009). The 2009 Plan has been reviewed at the time of writing and is now undergoing the process of review. A series of scientific investigations have been undertaken to improve understanding of the behavior of water resources in the Area that will inform the amended Plan. This paper presents the results of these investigations, and specifically: (i) the implications of a long-term changing climate, including a higher frequency of extreme events such as the recent drier conditions experienced since the Millennium drought, interspersed with the highly wet years in between such as 2016, 2021 and 2022; (ii) evidence of a possible shift in annual and seasonal rainfall patterns since the beginning of the Millennium drought, and their impacts on the Area's rainfall-runoff ('R-R') response; (iii) a consideration of these factors, and choosing an appropriate climate period for amending the Plan that allocates water for current and future consumptive needs and the environment over a 10-year life-cycle, and (iv) discussion on the implications on the aquatic ecosystems of the Area.

The outcomes discussed in this paper are recommended for consideration in other areas experiencing changing climate, including areas in South Australia where water plans are being reviewed.

2. BACKGROUND

The 2009 Plan includes an assessment of the capacity of surface water resources (‘Resource capacity’), to meet the various current and future demands and policies and principles for allocation and transfer of water. It also identifies the needs of water-dependent ecosystems and the impacts of development on these needs but stops short of establishing environmental water requirements (‘EWRs’) and Environmentally Sustainable Extraction Limits (‘ESEL’) as now required by the Act.

Surface water resource capacity for a catchment, or a prescribed area, is defined as the long-term mean annual runoff with the impacts of development (i.e., farm dams and watercourse extractions) removed through modelling. The choice of climate period used for calculating resource capacity, or in fact for establishing EWRs or ESELs, is less critical if the long-term climate follows a stable pattern. Given the highly variable recent climate and uncertain future climate, along with evidence of a drying climate projected into the future, choosing an appropriate climate period becomes more critical when reviewing and amending plans that were developed using climate data from a few decades ago. Resource capacity in the 2009 Plan was calculated using streamflow data for a climate period ending 2006.

The recent Millennium drought (‘drought’), spanning from 1997 to 2009, was a major climate event observed across Australia. It is considered to have had a major impact on water resources across the country (CSIRO, 2010). Numerous studies into the impact of the drought have since been undertaken, researching the R-R rainfall-processes of catchments pre- and post-drought. Results of the studies showed that in some areas, a catchment’s ability to produce runoff from a given amount of rainfall post-drought had returned to pre-drought conditions, while in others it didn’t return or the recovery was suppressed (DELWP, 2020).

3. RAINFALL TRENDS AND CHANGEPOINT ANALYSIS

Rainfall data for all available rainfall monitoring stations within the Area were retrieved from SILO (Queensland Government, 2023). Six stations in the Area are currently operational, with five of those possessing data records extending from at least 1950 – Greenock (23305), Lyndoch (23309), Tanunda (23318), Williamstown (23752) and Glen Gillian (23756). The data indicates there have been 8 to 9 ‘wet’ years (top 30 percent of rainfall years) compared to 4 to 6 ‘dry’ years (bottom 30 percent) experienced at the current long-term rainfall sites since the start of the drought period.

Statistical analyses were conducted on the data over monthly, seasonal and annual timescales from 1900 to present. Analysis using CUSUM and Bayesian changepoint detection (Dehghan Monfared and Lak, 2017) was conducted to identify step changes occurring in the data, as shown in the example plot in Figure 2. Wilcoxon rank-sum (WRS) test (Kaur and Kumar, 2015) and Welch’s t-test (WTT) (Zimmerman and Zumbo, 1993) were applied to determine the probability of a difference between the pre-drought and drought/post-drought periods, while the Mann-Kendall (MK) test (Wang et al., 2020) was used to assess whether consistent increasing or decreasing trends were present in the data.

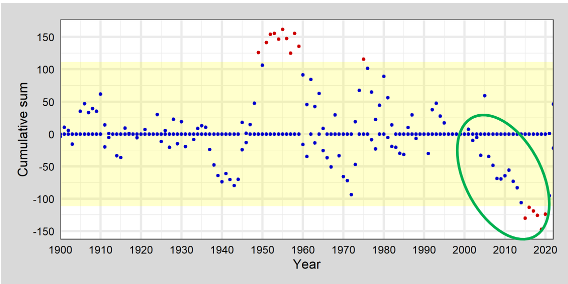


Figure 2. CUSUM analysis results for October rainfall totals at Tanunda (23318) with control limits in yellow. Step change suggested by circled data.

In general, evidence of a positive shift (increase) in rainfall was indicated during the 2010s in summer to early autumn months, driven predominantly by the high rainfall year of 2010. In contrast, little change was indicated during the higher rainfall months, with the exception of October rainfall, which showed the strongest evidence of a shift from the early- to mid-2000s (refer to Figure 2). Under an annual timescale, only a minor indication of a decrease in rainfall post-drought was noted.

The analysis additionally indicates rainfall moving back towards the long-term average at the end of the assessment period, owing to the higher rainfall totals experience in 2021 and 2022. Continued assessment will be required to determine whether this recent increase in rainfall is temporary or a sustained one.

4. STREAMFLOW

Streamflow records from the Yaladara (A5050502) gauging station located at the drainage point for much of the Area are used in the analysis. Streamflow data for the period 1977 to 2022 reflects rainfall variability, reaching peak discharge volumes of 64.5 GL (1992), and dropping as low as 0.5 GL (2018), with the long-term annual average being ~12 GL (Figure 3). The average annual streamflow has reduced by around 50% since the beginning of the drought. Catchment characteristics that influence runoff response vary spatially within the Area, with some sections of the Jacob Creek sub-catchment indicating perennial flows, and other sub-catchment streams flowing for less than 30% of the time (DEW, 2022).

Daily flow percentile exceedance for pre-, drought and post-drought periods for streamflow records at the Yaldara gauging station are plotted in (Figure 4). Data representing the individual percentiles are shown in the table inset, with the average number of flowing days per year for the different time periods shown in bottom row of the table. The number of flowing days per year and the low, medium, and high flow ranges are some of the key metrics that characterize the flow regime of a catchment. These metrics also form part of the suite of EWR metrics used to assess eco-system flow requirements and define ESELs in a Plan.

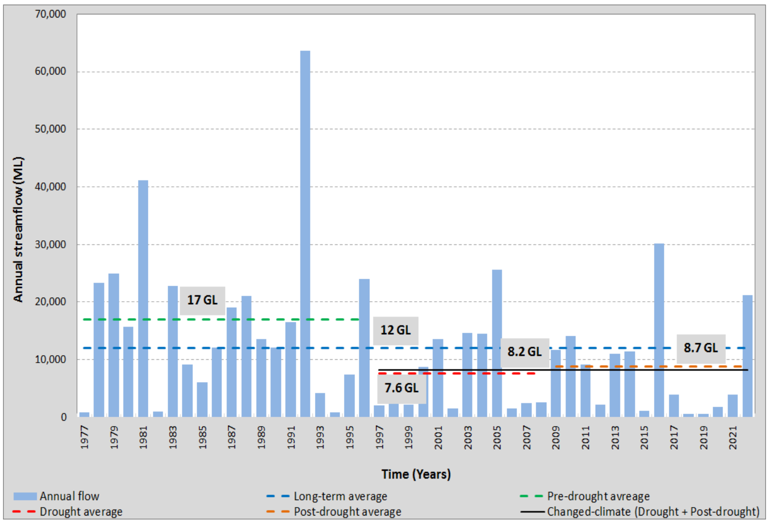
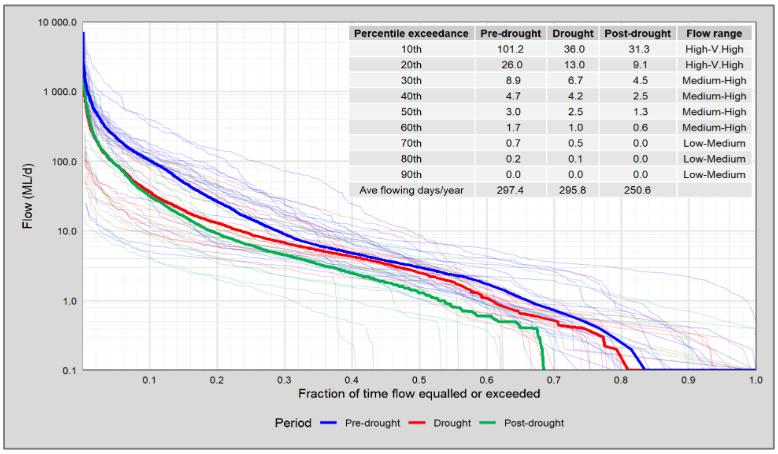


Figure 3. Annual streamflow at Yaldara gauging station

The average number of flowing days at Yaldara has reduced by 47 days per year since the beginning of the drought. This implies that the duration when the stream beds are dry has been extended by around 47 days per year, on average, since the beginning of the drought. These data also indicate that the entire flow regime was affected during the drought and continues to get worse, providing evidence of a shift or alteration of the Area's flow regime since the beginning of the drought. The environmental implications of this shift in flow regime since the drought are discussed further in section 7.



Percentile exceedance	Pre-drought	Drought	Post-drought	Flow range
10th	101.2	36.0	31.3	High-V.High
20th	26.0	13.0	9.1	High-V.High
30th	8.9	6.7	4.5	Medium-High
40th	4.7	4.2	2.5	Medium-High
50th	3.0	2.5	1.3	Medium-High
60th	1.7	1.0	0.6	Medium-High
70th	0.7	0.5	0.0	Low-Medium
80th	0.2	0.1	0.0	Low-Medium
90th	0.0	0.0	0.0	Low-Medium
Ave flowing days/year	297.4	295.8	250.6	

Figure 4. Daily flow exceedance curves – individual years (thin lines) and pre/drought/post periods (thick lines)

5. HYDROLOGIC MODELLING

With evidence of change occurring in both observed rainfall and flow data, modelling was conducted using climate projections to compare observed to long-term predicted flows in the Area. The Area is modelled in eWater Source modelling platform (eWater Ltd., 2013), and includes catchment features such as sub-catchments, storages (e.g., farm dams, reservoirs), demands (e.g., extractions from river or storages) and weirs (Jones-Gill and Savadamuthu, 2014; DEW, 2022). The model was calibrated using historical rainfall and evaporation data in periods where streamflow data were available, along with the estimated demands applied to the farm dams and watercourses, as detailed in Jones-Gill and Savadamuthu (2014). The Barossa Source model was used to simulate streamflow based on projected rainfall in the Area. Downscaled rainfall projection data from the 'SA Climate Ready' data set – developed by Goyder Institute for Water Research (2015) – was obtained for the Glen Gillian rainfall station (23756). This dataset contained two emission projections, namely an intermediate Representative Concentration Pathways (RCP) projection (RCP4.5), and a high RCP projection (RCP8.5), which correspond to atmospheric CO2 levels (by 2100) of approximately 550 and 940 ppm, respectively (DEW, 2022). A subset of three CMIP5 General Circulation Models (GCMs; IPCC, 2023) for the

Barossa PWRA were selected as detailed in DEW (2022), including mri.cgcm3 (least change from current), cnrm.cm5 (average change), and gfld.esm2m (greatest change). Each combination of emission projections and GCMs had 100 realisations of the downscaling model spanning from 2006 to 2100, with each realisation having a baseline period spanning from 1900 to 2005 for calculation of annual flow deviation from the baseline per realisation. The model was then run under a 'current use' scenario, applying present day extractions from the system over the full projection period.

Modelling indicates that current trends in the streamflow data are consistent with future predictions of a drying climate. Figure 5 shows a comparison of observed data from the Yaldara gauging station (A5050502) with projected streamflow. The median, interquartile range (IQR) and maximum and minimum flow values of all realisations were calculated annually, while 15-year moving averages were calculated on the observed and projected data (per GCM) separately to provide a longer-term indication of trends in the flow deviation data. The results suggest that the observed annual flow data generally aligns with the lower end of the modelled flows in the period of overlap (2006 to 2022). The 15-year moving average of observed data sits below those for each of the GCM projections, while overall trends in the modelled predictions suggest a gradual decrease in streamflow into the future.

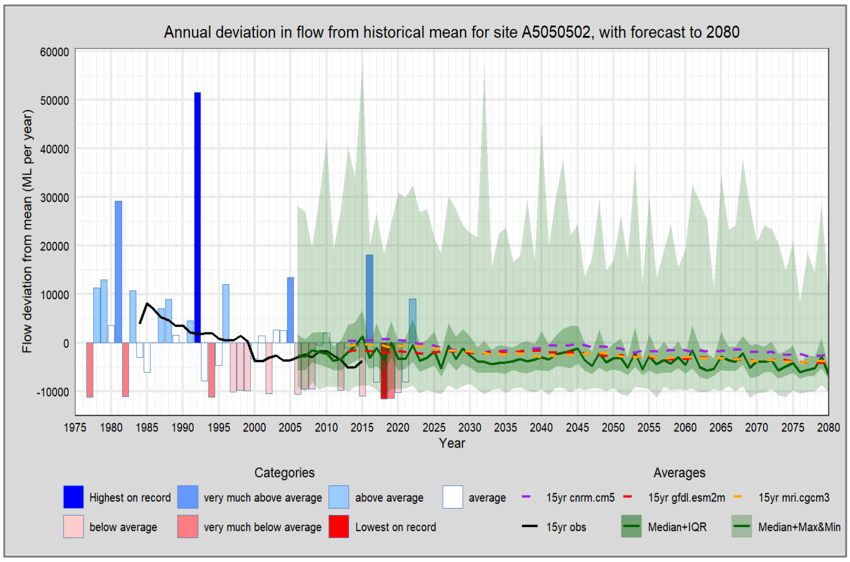


Figure 5. Observed and projected flows at site A5050502

6. RAINFALL-RUNOFF RELATIONSHIP AND RESOURCE CAPACITY

The rainfall-runoff ('R-R') response or relationship for a catchment is expected to be stable under stable climatic conditions i.e., a certain amount of runoff could be expected for a given amount of annual rainfall, taking into account the preceding year's rainfall. However, with a changing climate, which includes extended periods with changing rainfall patterns (seasonality and intensities) a shift in runoff response, is expected (Petheram *et al*. 2011; Tan and Neal, 2018). This has been reported for catchments across Australia, with some of them being classified as temporary, prolonged and permanent (Saft et, al., 2015; 2016a; 2016b).

The annual rainfall-runoff curve for the Area was fitted using flow records from the Yaldara (A5050502) gauging station and the rainfall records from the Area's representative rainfall station at Tanunda (23318). The curve, when fitted for the entire period of record (long-term 1977 – 2022), is shown as a blue colour in Figure 6. Taking into consideration the shift in rainfall since the commencement of the Millennium drought and the consequent changes in runoff responses, additional curves were fitted for pre-, drought and post-drought periods. It is quite evident from data plotted that there is a clear shift of the R-R relationship during the drought from the pre-drought period. Further, the R-R curves for the drought and post-drought periods are quite adjacent, indicating that the R-R response during those periods were quite similar and the runoff response is yet to return to pre-drought conditions. This provides further evidence for the shift in R-R response since the beginning of the drought. Consequently, use of the long-term R-R relationship in the amended Plan would result in overestimation of Resource Capacity and lack of recognition that the flow regime that has been altered since the Millennium drought. Based on the above, the combined drought and post-drought ('Changed climate') period has been recommended as the climate period for the amended Plan. Resource Capacity for Changed climate period is estimated at around 15,322 ML for the Area, which is 15% less than for the full period.

Reductions in rainfall have a non-linear and highly disproportionate impact on runoff or water availability which is further amplified in low rainfall catchments like the Barossa PWRA. The impacts on streamflow due to changes in rainfall – reflected in annual, seasonal, and monthly totals – are also amplified, resulting in a

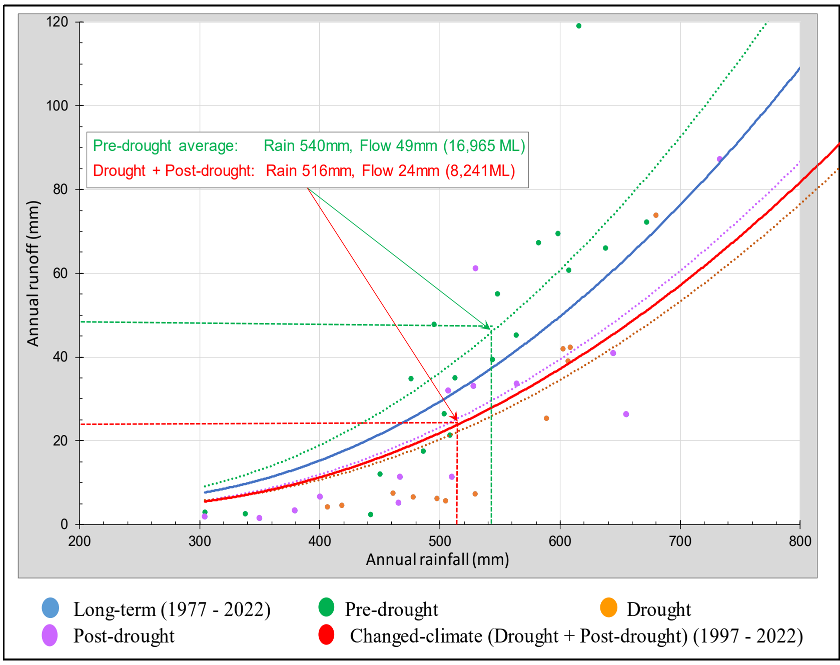


Figure 6. Rainfall-runoff relationship for the Barossa PWRA

higher reduction in catchment yields and alteration of streamflow patterns. A 4% reduction in average annual rainfall has resulted in around 50% reduction is average annual streamflow in the Area since the beginning of the drought. Given the nature of the rainfall-runoff response in drier areas like the Barossa, a small reduction in annual rainfall resulting in a much higher reduction runoff is to be expected.

7. ENVIRONMENTAL IMPLICATIONS

Assessment of key flow metrics associated with ecological condition has shown that in recent years the flow regime has shifted such that the maintenance of current ecological condition is at risk. While a degree of variability is expected, the variability now being observed is outside the expected range for the existing ecosystem with previously perennial sites (1970s and 1980s) ceasing to flow for several years at a time. The only flow-sensitive fish species remaining in the Area is the Mountain Galaxias (*Galaxias olidus*), which, once widespread in the area, are now isolated in a single small spring-fed tributary (Whiterod, unpub. 2022). Based on modelling undertaken to identify flow requirements for Mountain Galaxias, this remaining flow-sensitive species will be at increased risk and likely to be expatriated from the system as intermittency increases due to changing climate (Green et al. 2014). This increase in intermittency will also lead to a shift to more desiccant tolerant species and terrestrial vegetation within the river channel. For areas with significant groundwater interaction, the proliferation of invasive native plants such as Typha and Phragmites will continue (Nicol 2013, Maxwell et al. 2015). While increased extreme rainfall events may be of specific benefit for clearing monocultured vegetation, potential erosion issues associated with a cleared/poorly vegetated river channel will likely lead to long-term management complications and further environmental degradation.

8. CONCLUSIONS AND DISCUSSION

A climate period that incorporates the changes experienced over the past few decades, along with future climate projections, is to be considered when developing and/or amending water plans. Given the evidence of shift in climate and the rainfall-runoff response in the Barossa PWRA since the Millennium drought, and its alignment with projected future climate, the combined drought and post-drought (‘Changed-climate’) period has been recommended as the climate period to be used in the amended Water Allocation Plan for the Area.

The rainfall, streamflow (volume and pattern), rainfall-runoff relationship and surface water resource capacity data presented in this paper reflect the catchment behavior of the area during the Changed-climate period. Further scientific investigations are currently being undertaken to develop an environmentally-sensitive flow regime that represents the Changed-climate period. This will enable development of environmental water requirements, thresholds and environmentally sustainable extraction limits for the Area. While a shift in climate has been evidenced since the beginning of the Millennium drought (~ 2.5 decades), whether this shift is permanent or temporary and prolonged is uncertain and requires ongoing monitoring and evaluation, along with validation of climate projections when water plans are developed and/or amended.

The outcomes discussed in this paper, while relevant directly to this Area, are also recommended for consideration in other areas experiencing similar conditions of changing climate, including areas in South Australia where water plans are being reviewed.

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